CReDo

CATAPULT
Connected Places

STRATEGIC OUTLINE CASE

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Delivered in partnership with:

UKRI Innovate UK

CONTENTS

Authors

Chris Taylor | Connected Places Catapult
Friso Buker | Connected Places Catapult
Holy Neil | Connected Places Catapult

Acknowledging Phase 1 contributors

Centre for Digital Built Britain
Cambridge University
Joint Centre for Excellence in Environmental Intelligence
Crocodile Media
Department for Business, Energy & Industrial Stategy
Mott MacDonald
National Digital Twin Programme
ESRI UK

CReDo Project Partners

Delivered in partnership with: Innovate UK

INTRODUCTION

About CReDo

The Climate Resilience Demonstrator (CReDo) is a multi-year consortium innovation project developing a prototype digital twin for infrastructure resilience in the area of climate change adaptation. Specifically, it maps infrastructure networks' assets and their interconnections and dependencies within and between networks, in order to identify which assets are at most critical risk of "failure cascade" – whereby the failure of one asset triggers failures of other assets, amplifying the extent, duration and impact of service outage.

Currently, CReDo aims to support a strategic investment use case, whereby providing cross-sector insights to asset owners, the impact of resilience investments can be maximised. In this context, CReDo resolves asset failure caused by flooding across water, power distribution and telecommunication networks and uses this information to generate different economic-driven measures of vulnerability and criticality. More details are contained in this document below.

Asset owners (providing asset data and expertise as network owners)

Anglian Water
BT Group
UK Power Networks

Commercial and academic partners
(providing expertise as developers, data hosters, conveners and subject matter experts)

Centre for Digital Built Britain
Connected Places Catapult
CMCL Innovations
Edinburgh University
ESRI
Mott Macdonald
Newcastle University
Science & Technology Facilities Council
Warwick University

About this document

This document forms a Strategic Outline Case for the CReDo project, structured per the Five Case model, a standard public sector approach to forming business cases. Typically, the business cases progress through three stages: first a Strategic Outline Case to assess the overall fit with policy and objectives, and comparing expected societal benefits; then an Outline Business Case adding deeper detail including on procurement options, market readiness and cost projections; and finally a Full Business Case at point of contract award with deeper detail including full costings and risks to be managed. The purpose is to cover the main aspects of assessing a proposed project's viability and value for money whilst recognising that depth and details become available iteratively over time, as the project progresses.

The Five Cases are in summary:

1. **Strategic Case**
   Setting out the overall case for change, objectives and benefits
2. **Economic Case**
   Assessing the value of CReDo to different stakeholder groups
3. **Commercial Case**
   Considering supplier capability and risk appetite in the market to deliver CReDo
4. **Financial Case**
   Setting out considerations on funding sources and the main cost drivers of its development
5. **Management Case**
   Governance and management arrangement considerations for this stage of delivery

KEY FINDINGS AND TAKE-AWAYS

Case	Key points
Strategic	• Climate projections suggest that the number of infrastructure assets in areas with a high likelihood of flooding (1-in-30 annual chance or greater) will increase by at least 50% by the 2050s. • The economic losses from the winter 2019 to 2020 flooding were estimated to be about £333 million. But the economic damage avoided because of the protection provided is at least 14 times greater, at around £4.6 billion to £9.3 billion. • CReDo offers asset owners cross-sector views of asset interdependencies and criticality ranking, to enable more cost-effective resilience investment and cross-sector data sharing, designed to be compatible with the National Digital Twin Programme. • Intended benefits include fewer asset failures, fewer cross-network asset-failure cascades, reduced service outages for customers, more cost-effective resilience investment, avoided economic and environmental impacts and more.
Economic	• Considering purely the cost effectiveness of resilience measures recommended under CreDo, the Benefit Cost Ratio (BCR) of asset resilience investments is above 5 under the CReDo option. This entails between £51m and £538m of benefits with a Net Present Value of between £42m and £440m, depending on whether the pilot-to-UK scaling factor is based on proportion of population at risk of flooding or a conservative version of the same assumptions. • Those expected benefits include approximately £43m to £456m of avoided business costs, and between £7m and £79m of avoided lost consumer welfare, at national (UK) scale. • Avoided consumer losses and environmental externalities together form approximately 15% of the benefits – the public interest nature of CReDo's externality and consumer surplus benefits suggests the value of exploring whether public sector funding can support CReDo's initial development and / or market operation.

Case	Key points
Economic	• When including the development and maintenance costs of a national (UK) scale CReDo, Net Present Value may reach between £34m and £432m depending on the scaling factor used – equivalent to a BCR of more than 5 when using a conservative scaling factor or more than 55 when using a higher scaling factor. • There is evidence that benefits could be higher than modelled due to additional benefits that are not currently modelled, potential "network effects" of adding more networks, and the transferability of the pilot location's results. • N.B. the figures and net differences presented in the content below between the Intervention (CReDo) and the Counterfactual depend on a realistic Business As Usual which may be determined in future phases, as changes here will alter the expected net benefits. As such all figures are high level and indicative only at this strategic stage.

"We (networks) don't understand each other - we work in parallel. There will come a time when we need to work together - it is in everyone's interests. A digital twin is the missing piece of the jigsaw."(Asset Owner, water sector)

Case	Key points
Commercial	• Cybersecurity is an important topic for a digital twin such as CReDo, hosting data from multiple organisations and occasionally of a sensitive nature. External consultants holding expertise in the market may be consulted and engaged, as well as the use of distributed architecture to ensure CReDo is robustly developing in this area. • Until deeper design considerations are ready, and a go-to-market route reached, the commercial case is of limited applicability at this stage: procurement is not relevant to CReDo currently. • Rather, a key question is how it can be funded and drive revenues to be commercially sustainable, either through central or local government use, regulator endorsement / provision, asset owner subscription or varying models and combinations thereof.

Case	Key points
Financial	• It is expected that developing and maintaining a Minimum Viable Product (MVP) version of CReDo would require 1 year of development phase, with a cost of £3.3m (£2023). Beyond that, recurring maintenance costs are of approximately £0.4m per year. • A key challenge for CReDo is that whilst there is a clear set of benefits, they are fragmented across: beneficiaries who are not users; users who may benefit in ways disproportionate to their own investment; users who do not have mechanisms for cross-sector investment; different levels, remits and geographical boundaries of organisations. • Therefore, a key challenge facing CReDo's future is how to construct a commercially viable revenue model that not only delivers sufficient value to each participant, but is acceptable and realistic in terms of available budgets and spending objectives of the different organisation types who may use CReDo. Key revenue models consider the role of government authorities, regional utilities, national infrastructure owners, tiered access models – findings suggest value in combinations of user licensing and Pay As You Go models, with a corporate entity that continues to develop, maintain, support and enhance CReDo on an ongoing basis. • In the current context of high living costs, there may be a question of equitability. It could be argued that taxpayer funding will draw receipts disproportionately from the higher income brackets (due to higher tax rates), and that their corresponding marginal utility of income is lower than for lower income households, as each £ is valued more by those on lower incomes. Thus, funding CReDo from central government departments, because the source is ultimately the taxpayer, may offer equitability benefits in comparison to having asset owners pass costs on to the utilities' customers. This question remains to be explored further as part of future phases of revenue model definition and depends also on central government willingness, budget availability and departmental remit.
Management	• Managing diverse interests and technical development can come with risk and challenge. To ensure the long-term operation of CReDo, governance is envisioned to include Decision Making Board and Technical Advisory Groups, plus impartial direction and market co-ordination by a disinterested third party with additional expert inputs. • Notable opportunities for benefits realisation extend to additional use cases (extreme heat etc) and additional infrastructure networks to gain "network effects". • A detailed view of dependencies and next steps can be seen in the project's companion document, Developing CReDo from Demonstrator to a Market-Ready Tool.

Glossary

Terms

Some key business case terms used in this report:

Counterfactual	What would happen in the absence of the CReDo intervention
Discounting	Converting future values into an equivalent value in the present time period, in order to compare on a consistent basis.
Optimism Bias	The demonstrated, systematic tendency for benefit, costs and other estimates to be overly optimistic. To redress this tendency, adjustments are made to the relevant estimates.
Social Time Preference Rate	The rate at which society values the present compared to the future, as used in HM Treasury Green Book appraisals. .

Acronyms

Some acronyms used in this report:

BAU Business As Usual	The status quo or current situation, referring in this report to asset owners' resilience investment strategies and budgets.
BCR Benefit Cost Ratio	The ratio of discounted benefits to costs over time.
CReDo Climate Change Resilience Demonstrator	Climate Change Resilience Demonstrator.
NDTP National Digital Twin Programme	National Digital Twin Programme
NPV Net Present Value	The difference between the discounted benefits and costs over time.
MVP Minimum Viable Product	A version of a product with just enough features to be usable by early customers
RCP Representative Concentration Pathway	A set of assumptions about economic, social and physical changes that will influence climate change, used for modelling climate related scenarios. [3]
STPR Social Time Preference Rate	The rate at which society values the present compared to the future, used in discounting costs and benefits. [4]

STRATEGIC CASE: STRATEGIC CONTEXT

As climate change causes more extreme weather and rising sea levels, the UK's infrastructure faces a huge challenge: it was not designed with climate change in mind.

The systems that underpin our daily lives are increasingly susceptible to real-world issues, including major power disruptions, road blockages due to landslides, heat-induced impacts on trains, and flooding in crucial areas.

CReDo, a climate change adaptation digital twin that was developed in conjunction with Centre for Digital Built Britain and currently led by the Connected Places Catapult (CPC), looks specifically at the impact of extreme weather, in particular flooding, on energy, water and telecoms networks. Serving as a platform that integrates data from various infrastructure assets to simulate the repercussions of severe weather occurrences, it considers the interconnectedness of these assets, both within and across infrastructure boundaries. Climate projections suggest that the number of infrastructure assets in areas with a high likelihood of flooding (1-in-30 annual chance or greater) will increase by at least 50% by the 2050s. CReDo has the capability to predict which assets may experience failure during extreme weather events and how these failures could potentially affect other assets, considering their dependencies.

This holistic view of the cross-sector impact of extreme weather events enables asset operators and regulators to make decisions which maximise resilience across the infrastructure system rather than from a single sector point of view.

The economic losses from the winter 2019 to 2020 flooding were estimated to be about £333 million. But the economic damage avoided because of the protection provided is at least 14 times greater, at around £4.6 billion to £9.3 billion. CReDo offers the opportunity to improve key infrastructure resilience even further, by giving asset owners the opportunity to understand and plan for the impact of future climate emergencies and the interconnectedness across sectors. As emphasised by Julia King, Baroness Brown of Cambridge, "Asset owners really need to know who they are dependent on – it's crucial both for the integrity of assets but also for the service you give your customers. Understanding the risks in advance and how we can mitigate them is key."

Overview of the project

CReDo has been uniquely developed by a consortium of industry, government, and academia. The collaborative efforts of organisations with shared goals puts emphasis on the importance of integrating data across crucial infrastructure sectors to enhance decision-making and bolster climate resilience.

- **Phase 1** was led by the National Digital Twin program in collaboration with the Centre for Digital Built Britain (CDBB). The project initially focused on establishing a proof-of-concept connected digital twin. The digital twin was constructed using confidential asset data and synthetic data for demonstration purposes and replicated water, telecoms and energy infrastructure networks in the region of East Anglia. Its primary purpose was to simulate the impact of a particular type of flooding scenario, specifically surface water flooding, on these infrastructure networks.
- **Phase 2:** saw CReDo transition to a working prototype. In this stage, asset operators gained the capability to access real data and insights generated by the CReDo platform. Phase 2 focused on the "planning for resilience" use case, providing asset owners with insights to improve infrastructure resilience in the face of climate change impacts.

Using confidential asset data, the project expanded its geographic coverage to encompass a broader area within East Anglia. Phase 2 introduced the capability to model the impact of various flooding scenarios, making it more versatile in assessing and preparing for a range of potential climate-related disruptions.

Thus far, the project has brought together Anglian Water, BT Group, and UK Power Networks (UKPN) with a data exploration license arrangement from UKPN. These organisations have worked in collaboration with CPC to shape and develop CReDo for testing.

Background on national strategy and policy, business strategy and policy

At a network level, the present and intensifying effects of climate change impact on UK infrastructure networks in ways that induce costly inefficiencies, asset failures and service outage. The UK Government defines national infrastructure as the systems, sites and networks necessary for the "functioning of the country and the delivery of the essential services upon which daily life in the UK depends", identifying nine sectors:

1. **energy ***
2. **transport ****
3. **water ***
4. **communication ***
5. **food**
6. **health care**
7. **emergency services**
8. **financial services**
9. **government ****

* = current networks included within CReDo pilot

** = networks potentially included next in the near future

Within each sector, climate adaptation plans outline the most critical challenges faced by the steady increase in adverse weather conditions, including as a non-exhaustive snapshot issues from extreme heat such as pole termination failure due to heat waves, substations and tunnels at risk from higher temperatures, fluid-filled cables at risk of failure due to ground temperature changes; substation and network earthing systems adversely affected by summer heat and drought conditions; transformers affected by temperature rise; transformers affected by urban heat islands and coincident air conditioning demand.

Further, the same networks state the need for mitigation on flooding-induced asset failure, including issues from fluvial river and coastal flooding; substations affected by sea flooding due to increased rainstorms and/or tidal surges' precipitation flooding; substation failure affected by flooding due to nearby watercourses, heavy, rain, sea level rise and/or dam bursting as a result of increased winter rainfall.

This is not expected to remain a static issue: the Climate Change Committee's Adaptation Sub-Committee estimates that the number of assets in areas with a high likelihood of flooding (1-in-30 annual chance or greater) may increase by at least 50% by the 2050s. During storms and flooding in winter 2013/14, over 2 million customers suffered power cuts, of which 16,000 were without power for more than 48 hours.

Storm Arwen brought extremely strong winds with gusts exceeding 90 mph in some locations. What made this storm particularly impactful was the unusual direction of the winds, coming from the North, which is not typical for storms in the UK. These strong winds were accompanied by freezing temperatures. Storm Arwen left approximately a million homes and businesses without electricity. Some 40,000 homes remained without power three days after the storm, and it took ten days to fully restore power to all households. The disruption to electricity supply had significant economic impacts, particularly for businesses that rely on consistent power, such as manufacturing and retail.

In response to the storm's impacts and the performance of Distribution Network Operators (DNOs) during the incident, the Office of Gas and Electricity Markets (Ofgem), which regulates the gas and electricity industry in the UK, initiated a review. This review aimed to assess how well DNOs communicated with customers and how effectively they responded to and managed the storm's aftermath. The regulator concluded that the existing arrangements did not fully acknowledge the impact of extended power cuts on affected consumers.

It sought to ensure that lessons were learned to improve future storm response and customer communication.

The economic impacts of Storm Arwen were substantial, including lost productivity and revenue for businesses, costs associated with repairing infrastructure, and potential insurance claims. Experts at PWC suggested these could total more than £250m.

Additionally, Ofgem's regulatory review signalled the need for improved preparedness and response measures in the face of extreme weather events to mitigate future economic disruptions. As a result, the regulator announced this month that compensation for households and businesses that lose power due to severe weather events will rise to a maximum of £2,000 - up from £700 . This means that network companies that fail to follow the rules and protect consumers' interests by better preparing assets could face multi-million-pound fines. Separately in 2019, Ofwat required a water company to pay £126 million for breaching environment commitments: a fine of £3 million and £123 million returned to customers.

The role of data-driven enablers in industrial growth and resilience planning is recognised across central government policies, strategies and roadmaps, which form the basis of digital initiatives such as the National Digital Twin Programme (NDTP).

CReDo aligns with the National Digital Twin Progamme in terms of seeking to demonstrate the value of sharing data securely across organisations and taking a distributed approach to share that data.

CReDo is being developed so that it can be compatible with the National Digital Twin as it emerges.

THE CASE FOR CHANGE

Objectives to be achieved:

CReDo's early phase objectives were two-fold , to boldly demonstrate:

- **The benefits of using connected digital twins to increase resilience and enable climate change adaptation and mitigation, and**
- **How principled information management enables digital twins and datasets to be connected in a scalable way as part of the development of a Data Sharing Framework.**

The concept is driven by these core objectives, alongside a set of wider intentions that guide the project's focus and serve as key milestones on the path to realising its vision:

- **Enhance climate change understanding and encourage climate change adaptation decision-making as standard practice, promoting resilience, robustness, and the mitigation of cascading risks across sectors.**
- **Develop probabilistic failure mode models, identifying vulnerabilities, allowing for targeted resilience improvements.**
- **Support cross-sector collaboration and data sharing**
- **Integrate economic and societal cost data to quantify the implications of failure, such as recovery costs, repair expenses, and impacts on supply continuity.**
- **Scalability; across water, telecoms, and energy networks across the UK**

Using an agile approach since development, the project has evolved from a primary emphasis on acquiring knowledge about cross-sector data sharing to a more nuanced exploration of the intricate interconnectedness within infrastructure systems and their susceptibility to future weather events. Research endeavours have shifted towards gaining a deeper understanding of how these systems are interrelated and how they may be influenced by climatic extremes.

Exploration has not only ventured into areas not comprehensively understood before but also facilitated the exchange of data in these underexplored domains. This has not only enriched our knowledge base but has also added substantial value to research, underscoring the critical significance of resilience and the role played by cross-sector collaboration in bolstering our infrastructure systems.

However, a persistent challenge that the industry continues to grapple with is the absence of comprehensive tools to accurately quantify the advantages and value associated with resilience. This issue highlights the imperative need for further research and development efforts in this crucial domain, as it holds the potential to drive more informed decision-making and ensure the long-term sustainability of our infrastructure systems in the face of climate change challenges.

Existing arrangements

The current systems and tools used for modelling weather-related asset failures varies from asset owner to asset owner. Some model how flooding failures affect assets, in their network only and others do no specific modelling (though they do have an in-house experience-based understanding of the assets most at risk). Typically any modelling does not capture the full picture of private costs and welfare losses, suggesting any decisions on which assets to invest in are likely to be made on imperfect information about the full costs of individual (and cross-sector) asset failures. Tools do exist to support such decisions but can be highly fragmented – one asset owner has reported that their colleagues in the Resilience teams must deal with up to 15 competing tools. Each partially provides a subset of data needed to assess overall criticality yet is insufficient in itself.

Climate change is seen as a present and increasing threat, with published adaptation strategies enumerating the ways that different asset types are at risk from high temperatures, floods and other weather-related events. Opportunities are seen here for sharing data and working across sector boundaries ("We need to collaborate – we can't keep working in a bubble" – asset owner, CReDo interviews). Yet the real and perceived risks around data sharing result in some organisations taking a default position of no data sharing beyond the minimum regulatory requirements, and no cross-sector decision-making of depth.

CURRENT AND FUTURE BUSINESS NEEDS

Damage to critical infrastructure as a result of the ever-increasing threat of climate change have both direct and indirect social and economic impacts on government, industry and individuals.

Impacts on Government

Central government, as the largest source of flood and coastal erosion risk management (FCERM) funding in England, contributed around 90% of funding in the financial year ending 2022. Expenditure of the FCERM in England increased from £777 million in 2018 to £1.063 billion in 2021. Some of the key impacts to government include:

- **Infrastructure Repair and Replacement Costs:** Climate change-related events such as flooding, hurricanes, and extreme weather can cause damage to critical infrastructure such as roads, bridges, airports, and utilities. The government is responsible for funding the repair and replacement of this infrastructure, which can be extremely costly. These expenses can strain government budgets and resources.
- **Emergency Response Costs:** When climate-related disasters occur, governments often incur significant costs associated with emergency response efforts. This includes expenses related to deploying first responders, conducting search and rescue operations, providing shelter and medical care, and managing evacuation procedures. These emergency response costs can be substantial and can quickly deplete government funds.
- **Loss of Tax Revenue:** Climate-related damage to critical infrastructure can disrupt economic activity, leading to a loss of tax revenue for the government. Businesses may struggle to recover from climate-related disruptions, leading to reduced profits and tax contributions. This can impact the government's ability to fund essential services.
- **Impact on Government Finances:** The cost of climate change-related damage to critical infrastructure can have long-term implications for government finances. It may necessitate borrowing, increase public debt, or divert funds from other government programs and initiatives. This can lead to difficult decisions about resource allocation and budget prioritization

Overall, the economic impact of climate change-related damage to critical infrastructure on the government can be significant, affecting public finances, services, and long-term planning.

It underscores the importance of proactive climate resilience and mitigation strategies to reduce the financial burden on governments and protect communities and critical assets from the growing risks associated with climate change.

Impacts on Industry

The 2007 floods cost £325 million in disruption to the provision of goods and services in England and Wales.

This represented 60% of the total estimated economic costs of the flooding associated with impacts on important national infrastructure, the remainder being the direct physical damages to infrastructure assets, costs mostly carried by the organisations (and indirectly their customers) that own them. The pressure is on for industry to enhance its understanding of the impacts of climate change on their infrastructure systems. If nothing is done, the lack of awareness and preparedness for cascading failures in connected systems could lead to severe disruptions in critical infrastructure networks. This could result in extended power outages, water supply disruptions, and communication failures, with significant economic, societal, and safety consequences.

In October 2011, more than seven thousand properties in Birmingham were left without electricity following a power cut which also caused service outages in nationwide broadband service. The fault at the major exchange meant a loss of internet service for customers in several parts of the country, including Cardiff, Bristol, East Yorkshire and London. Disruptions such as these have direct impacts on both customers and businesses:

- **Reputation Damage:** Service outages, especially those of a nationwide scale, can severely damage the reputation of service providers. Customers expect reliable and uninterrupted service, and any significant disruption can lead to a loss of trust and confidence in the company.
- **Financial Consequences:** Service providers may face financial repercussions in the form of compensation claims from affected customers. They may also incur costs associated with resolving the outage, such as repairs, maintenance, and communication with customers.
- **Regulatory Scrutiny:** Regulatory authorities may investigate such outages to ensure that service providers have adequate backup systems and disaster recovery plans in place. Fines or penalties could be imposed if it's determined that the provider's infrastructure and contingency measures were insufficient.
- **Customer Churn:** Prolonged outages can lead to customer churn, as frustrated customers may decide to switch to alternative service providers. Retaining and regaining customers after such an incident can be challenging.

In addition to the above examples, Table 1 below sets out a summary of damages and disruption to services and businesses from flooding, from a subset of cases in England since 2013.

Month/	Cause	Area/Location	Impacts
December 2013	Heavy rainfall, storm, coastal surge	South East England (Dorset, Hampshire, Kent, Surrey)	£1.3 billion worth of economic damage, 6,000 people affected, transport disruption, 4,500 ha of coastal conservation sites affected, damage to seaside peers
January-February 2014	Heavy rain, storms	East Coast (Somerset, Cornwell, Dorset, Devon)	7,000 people affected, £19 million in agricultural losses, interruptions to critical infrastructure, disruption to transportation and emergency services, insurance losses of £1.5 billion yearly
December to January 2015/16	Winter storms-Storm Desmond	Northern England (Wales, Bangor, Anglesey, Swansea)	£1.6 billion economic damages, 36,000 people affected, £15.5 million agricultural losses, major infrastructural disruption, 70 sewage treatment works inundated
July-August 2017	Heavy rainfall	Eastern/South Eastern England (Berkshire, Kent, Cornwall, Norfolk, Wiltshire, Hertfordshire, Leconfield)	Transport disruption in many towns due to flooded roads, localised damage to residential and commercial buildings
May 2018	Heavy rainfall	East/West Midlands (Walsall, Lapworth, Hockley, Rugby)	One death, extensive transport disruption, disruption of businesses/ services, damage to properties
March, June November 2019	Heavy rainfall (Storm Ciara)	North, East, Midlands, South/ South East (Lincolnshire, Skegness, Boston Yorkshire, Fishlake, Doncaster, Worksop)	One death, extensive destruction of property, disrupted transport and services, hundreds displaced from their homes
February, August, November, December 2020	Storms (Dennis, Francis, Bella)	Large swathes of England (Worcester, Telford, Shrewsbury, East Yorkshire, Cornwall, Shropshire, Bewdley, Lancashire, Cheshire, Oxfordshire, Northamptonshire	5 fatalities, transport disruption, homes evacuated, flood defences overtopped, downed trees/power lines, thousands of houses without electricity, closure of caravan parks, significant insurance pay-outs
January, February 2021	Storms (Christoph, Darcy-snow)	South East, Cumbria, Rochdale, Preston, Lancaster, Cornwall, Warrington, Northwich, East Anglia,	More than 3,000 families evacuated, heavy snow disrupted transportation services and businesses, landslide, thousands of homes left without power

Table 1. Damages and disruption to services and businesses from flooding, subset of cases in England since 2013

POTENTIAL SCOPE AND SERVICE REQUIREMENTS

CReDo is designed as a digital twin that maps the assets and asset connections between infrastructure networks, enabling holistic insight into cross-sector interdependencies and - crucially - the cascades of multiple asset failures that can result from any single asset outage.

Climate change data

In the content of climate change, CReDo's asset failures are modelled according to probabilistic flood models for different types and depths of floods. Flooding data used in the model for real-world analysis is provided by Fathom. The dataset itself has many different scenarios:

- **three emission scenarios,** namely RCP26, RCP45 and RCP85 (Representative Concentration Pathway). The scenario used in CReDo's model is RCP85.
- **flooding data** based on year 2030, 2050 and 2070. Because the evaluation period is between 2030 and 2050, 2050 data was chosen.
- **three different flooding types:** coastal, pluvial and fluvial. All three are used in CReDo's analysis
- **flooding probabilities:** "return periods" ranging from 1-in-5 year floods, up to 1-in-1000. Return periods used include: 15; 110; 120; 150; 175; 1,100; 1,200; 1,250; 1,500; 11,000
- **spatial resolution** of flood data in 10-meter x 10-meter grids

Asset data

CReDo models the interconnections between network assets based on asset type, location, upstream and downstream dependencies, current resilience measures, potential additional resilience measures and other data.

Economic data

Inputs required for cost calculations, for example, willingness-to-pay factors, costs of preventative measures and containment measures, consumer compensation payment parameters etc.

Algorithms and user interface

Specifically, CReDo can surface to the user insights drawn from components including:

- **Failure models** to understand the effect of weather hazards on individual assets, and then propagating the knock-on failures through the combined system
- **Economic models** to approximate the expected costs to network operators (including business costs, regulatory costs, externalities, producer and consumer surplus losses etc)
- **Decision models** to optimise investment allocation, by testing the resilience of the network under different decision models and through algorithmic cost-benefit analysis

MAIN BENEFITS AND RISKS

Impact mapping sessions with key internal and external stakeholders have identified the main benefits expected for different stakeholder groups and shown the linkages in the logic models below. These are explored and, where viable, quantified in terms of economic costs and benefits in section 3 “Economic Case”.

Stakeholder group	Expected outcomes
Asset owner	• **Reduced severity of outages** (including number of assets, frequency, duration) • **More coordinated infrastructure investment decisions** by decision makers, resilience planning on a national scale • **More effective resilience plans** for disruptive weather events • **Reduced cost of repairs** / cost of response to disruptive weather events • **More effective investment**, lower cost for greater (system) resilience • **Reduced burden** of regulatory costs • **Improved asset utilisation** and service delivery • **Reduced cost of data sharing** • **Improved internal resilience decision making**, due to increased access to information • **Improved collaboration across other sectors**, due to the value of secure data sharing • **Reduced burden of reporting to regulators** during Price Reviews etc.
Regulator	• **Deeper and more consistent insights** across asset owner networks
Customers	• **Avoided damage** to property (failed pumping station overflows etc) • **Avoided loss of income** to businesses / Working From Home customers • **Reduced disruption** to service • **Increased resilience /** reduced loss to of essential infrastructure (schools, hospitals, roads) • **Reduction in flood related contamination /** pollution (e.g. sewage overflow into rivers etc)

Object 1: Climate Resilience

Rationale for Intervention
What problems are being addressed?
What is the gap in the market/ market

Cascade risk: vulnerabilities in one infrastructure sector can have severe consequences to other sectors in the supply chain

Limited sector understanding of interdependencies, between their assets, networks, and those in other sectors

Climate change increases the risks of adverse weather events

Inputs
What activities and resources are needed?

Data from collaborators:
- asset owners
- flood model data providers

Data platform:
- hosting
- accessing
- modelling
- reporting

Stakeholder collaboration:
- mapping
- user engagement (interviews, workshops)

Resource and time costs:
- software developers (platform)
- data scientists (moedls, asset owners)
- industry experts (development pathway)
- industry stakeholders (insights)

Outputs
What product/ service is produced?

CReDo digital Twin

Model expected impact of disruptive events

Provide decision intelligence on how to respond and adapt to improve overall system resilience

Intuitive user interface (e.g. maps, dashboards etc,)
- Failure models to understand the effect of weather hazards on individual assets, and then propagating the knock-on failures through the combined system
- Economic models approximate expected costs to network operators (CapEx, OpEx, regulatory fees, productivity and societal losses)
- Decision models optimise resilience of the network through algorithmic cost-benefit analysis
- Planned / in-development feature - dynamic modelling - time or duration of flooding is not currently modelled. CReDo will need to model the time resolution of the failure events due to some of the failure mechanisms being inherently time dependent (e.g. how long will a reserve power supply last)

Outcomes
What benefits/dis-benefits are expected for different stakeholder groups in the short and medium term?

Improved response to flood events by asset owners (better targeting of priority assets, faster responses) leading to:

Reduced severity of outages :
- number of assets involved
- frequency
- duration
- cascade

Improved understanding of climate impacts, for as: owners, as CReDo is showing climate scenario data tt otherwise might not be seen

Improved understanding of interdependencies of as: between sectors, for asset owners

Improved planning of flood intervention measures: asset owners, due to better understanding of where th maximum benefits come from at the system level. Thii: includes for new assets and also in current asset base modification.

More coordinated infrastructure investment decisions by decision makers (who - gov, regulators, asset owners?) (resilience planning on a national scale).

Impacts: What benefits/disbenefits are expected for different stakeholder groups in the long term?

Economic: Asset Owners
- More effective resilience plans for disruptive weather events
- Reduced cost of repairs/cost of response to disruptive weather events
- More effective investment, lower cost for greater (system) resilience
- Reduced burden of regulatory penalties
- Reduced burden of reporting to regulators -price review etc.

Economic: Commercial & Residential Owners
- Avoided damage to property (failed pumping station overflows etc)
- Avoided loss of income to businesses / Working From Home customers

Social: Commercial & Residential Owners
- Reduced disruption to service
- Avoided injuries/ deaths/ mental health issues (commercial)

Social: Wider Society
- Increased resilience of essential infrastructure -schools, hospitals, roads
- Reduce loss to critical sectors, e.g. NHS, hospitals

Environmental: Wider Society
- More effective resilience to disruptive weather events
- Improved resilience decision making
- Reduction in flood related contaminatior / pollution (e.g. sewage in the rivers)

Figure 1. Logic Model Part 1, Climate resilience

Objective 2: Data Sharing Framework

Rationale for Intervention What problems are being addressed? What is the gap in the market/ market	Inputs What activities and resources are needed?	Outputs What product/ service is produced?	Outcomes What benefits/dis-benefits are expected for different stakeholder groups in the short and medium term?
Limited data sharing by critical national infrastructure sectors, hindering the value and improved decisionmaking that can come with collaboration	**Exploration of information management** and data sharing good practice	**Demonstration** of how data sharing might be used to extract more value and make better decisions **Development** towards more scalable, distributed, federated approach	**Increased trust** between parties over data sharing **Established mechanisms for sharing data,** e.g: • data sharing agreements, data licenses • distributed architecture **Increased willingness to share data** between sectors, due to cultural change fed by data availability and trust **More efficient information sharing between organisations** (asset owners, regulators, public bodies etc., different access rights) **Organisations sharing data** to be utilised for use cases outside their direct sphere of influence **Reduced barriers to cross-sector innovation** and digitalisation from enabling better data integration between systems and digital twins.

Impacts: What benefits/disbenefits are expected for different stakeholder groups in the long term?

Economic: Asset Owners	**Economic:** Other Sectors	**Social:** Residential/ Commercial Customers	**Environmental:**
• Reduced cost of data sharing • Improved decision making, due to increased access to information • Lower cost of providing services to customers	• Accelerated development of digital twins • Reduced cost of developing digital twins • Improved collaboration across other sectors, due to the value of secure • data sharing • Improved decision making, due to integrated perspective • General Spillovers • Progress discussion on climate change modelling • Better quality data • More accessible data	• Improved quality of service • Lower cost of service • General spillovers • Increased awareness of climate change resilience	• Spillovers from application of best practice data sharing - enables asset • owners to address other areas where data sharing is required - e.g. pollution • reporting

Figure 1. Logic Model Part 1, Climate resilience

Figure 1. Overview gap analysis of CReDo to MVP state.

MAIN CONSTRAINTS AND DEPENDENCIES

Despite the potential benefits, CReDo also faces some potential constraints in its delivery and realisation of those benefits:

- **Data readiness in asset owners:** asset owners have varying levels of work done already on their data in order to make it shareable – where little work has been done, preparing data may come at cost, as personnel in the organisation will need to assess quality, data feed problems, maintenance and update protocols etc.
- **Quality of currently available climate data** poses a barrier, as more manipulation may need performed beyond existing datasets, and more insights would be beneficial (e.g. "time resolved" durations of flood data not currently available ot the tool). This includes data for all potential climate phenomenon types of interest and how to combine the effects of these onto the infrastructure.
- **Collaborative data sharing:** scalability is needed in licenses in order to enable new network operators to join the tool, and restrictions overcome around sharing data back to users from CReDo
- **Sector investment mechanisms:** are not currently set up in a way to actively encourage or facilitate cross-sector investments amongst asset owners.
- **Limited availability for climate resilience innovation funding:** some sectors have different funding opportunities and scales available than others.

These high-level barriers and constraints are explored in more detail in the Economic and Management Cases on the following pages.

ECONOMIC CASE: METHODOLOGY

This section of the report considers the net value of different options for asset owners and to society for the understanding and reacting to the resilience of critical infrastructure networks compared with a Counterfactual scenario.

Options

In order to model the value of money of the proposed CReDo option, its Net Present Value (NPV) and Benefits Cost Ratio (BCR) are assessed against an assumed counterfactual (what would happen in the absence of CReDo). The options are specified below:

Connected Digital Twin CReDo (Intervention)

The proposed intervention. A cross-sector digital twin with a full systems-view of asset criticality, based on cross-network interconnections. The decision model for making resilience investments is for CReDo to model the interconnections and criticality rankings of all assets in all available asset owners' networks and make prioritised investment recommendations accordingly – the Benefit Cost Ratios for each investment are ranked and prioritised.

Blanket Investment, Low-Mid Budget (Counterfactual)

The assumed counterfactual against which to compare CReDo. The decision model for making resilience investments is for asset owners to make blanket investment across all assets with no prioritisation considered.

Where alternative measures are available for an individual asset, they invest on the middle-cost measure (if 3 measures are available) or the low-cost measure (if 2 measures are available). This option relies on assumptions about the decision models and budget constraints in asset owners (see section 3.1.4 "Model limitations" below describes the challenges and related assumptions).

No Investment

A hypothetical option that enables a consistent comparison of the above two options. It models the expected assets' service failures and resulting economic impacts under the conditions that no further investment is made beyond the existing resilience levels of the assets. Whilst not a realistic real-world scenario is itself (asset operators, regulators and other bodies already have resilience budgets, teams and strategies), it enables the net gains from the CReDo and Blanket Investment options to be compared like-for-like, by each being assessed against the impacts under Do Nothing conditions. More detail is given directly below.

Benefits modelling

Under each option, the benefits are modelled in CReDo based on the probabilities of different flood types occurring and the current resilience levels of the assets, and the asset failures quantified in £ values based on Total Economic Cost. Total Economic Cost is comprised of the private costs to asset owners and the lost economic surplus to producers and consumers arising from asset failures, including environmental externalities. These costs are modelled according to the Phase 2 assessment approach put forward by Frontier Economics and produced from the CReDo tool using real data from the three participating asset owners representing water, telecommunications and electricity distribution networks. The Total Economic Costs under each option is then compared to the Total Economic Costs under the No Investment option, to allow like-for-like comparison.

The private business costs depend on the physical and operating characteristics of the assets that are affected by the flood, and the severity of the flood. Such costs include preventative costs (associated with preventing asset failures, for example the incremental costs of reinstalling the level of an asset above flood risk height) and containment and restoration costs (associated with responding to asset failures, for example the operating costs of running back-up generators to maintain power supply).

The lost economic surplus is based on the loss for producers from being unable to sell their services above their minimum selling price and the welfare loss to customers from asset outages because they no longer receive a service that they value above the price that they are billed for. Some additional potential impacts such as foregone surplus were not included in the model (see section 3.1.4 "Model limitations").

Model considerations

The appraisal tables and analysis below leverage the pilot study data, methodology and findings, with additional analysis from CPC data science team refining the algorithms, datasets and visualisations. Findings are based on the following considerations:

Geographical boundary:
- the pilot took place in an area covering part of Norfolk and Cambridgeshire, with approximately 200,000 population, 80,000 households and 4,056 assets mapped.
- In the tables and commentary below, the findings are scaled to national (UK) scale using scaling factors described below, in order to compare potential benefits with potential costs.

Asset owners:
- three asset owners, each representing the water, telecommunications or electricity distribution networks (Anglian Water, BT Group and UKPN respectively).

Base year:
- all figures in £2023 prices and values.

Time period:
- benefits and costs are calculated until 2050 to align with Net Zero targets, with resilience investments assumed made in 2029 and benefits occurring the following year. The year 2029 was chosen during Phase 1 to align with Price Review and Price Control cycles (and therefore spending objectives).

Social Rate of Time Preference (STRP)
- all figures discounted according to HM Treasury guidance in the Green Book guide to appraisal, at 3.5% per year. Discounting is a technique used to compare costs and benefits occurring over different periods of time on a consistent basis, based on the concept of time preference – that generally people prefer to receive goods and services now rather than later.

Optimism Bias:
- 61.8% applied to capital expenditure costs based on the mitigations status of standard contributory factors given by HM Treasury's Green Book. 10% assumed for operational expenditure. Not applied to benefits on the basis that currently quantified benefits are expected to underreport important impacts (for example, foregone economic surplus, details explained in the appraisal below). Optimism Bias refers to the demonstrated, systematic tendency for benefits, costs and other estimates to be overly optimistic. To redress this tendency, adjustments are made to the relevant estimates.

Budget constraint:
- the size of budgets for asset resilience investments is not available at the same geographical area as the pilot (Norfolk) or for the same functional use case (flooding only). Therefore, CReDo is used to model the optimal budget constraint.

Cross-sector view:
- figures based on cross-network interdependencies and impacts.

Where figures in tables or analysis relate to any other scale or assumptions, it will be stated directly (for example, if indicative figures refer to a national scale CReDo, this will be directly referenced).

MODEL LIMITATIONS

Limitations

Some limitations are recognised in the model at the project's Strategic Outline Case stage:

1. **Asset owner investment budgets:** the pilot was angled at a specific sub-regional area in Norfolk. Whilst local assets and their interconnections with other networks (and households and businesses etc) can be modelled, there is no publicly available data on the investment budgets that align with the same geographical boundaries as the pilot area, or with the same functional definitions as the pilot use case (i.e. resilience budgets solely for flooding induced asset failures). As a result, any calculations which rely on non-available budget or cost data such as Net Present Value or Benefits Cost Ratio are not present in the analysis tables for the Counterfactual option, and will be represented by an "NA" in the appropriate cell.

2. **Asset owner investment strategies:** at this stage of the project, data collected in the CReDo model does not include the asset owner's own views of their asset criticality rankings.

3. **Foregone economic surplus:** the Phase 2 appraisal methodology's Total Economic Cost includes asset owner business costs and lost economic surplus, itself comprised of producer surplus, consumer surplus and externalities (see the definitions described in section 3.1.2 Benefits above). Under that methodology, it was assumed that producer surplus for the current set of asset operators is zero and the consumer surplus was proxied by willingness-to-pay (WtP) per unit of service, multiplied by the number of customers affected and the duration of the outage. There are additional impacts that may not be captured in the current model, for example the foregone economic surplus of asset owners' commercial customers being unable to carry out business activities. In practice asset owners may have containment measures to mitigate this (for example water networks may use trucks to deliver water to high usage businesses like breweries or vulnerable customers like hospitals), but any additional foregone surplus is not included. Therefore, benefits could be expected to be higher than the current model produces. As Ofgem noted following Storm Arwen in 2021, the customer compensation arrangements in place did not fully acknowledge the impact of extended power cuts on affected consumers.

4. **Customer compensation payment limits are expected to increase:** Ofgem has recently announced that maximum compensation to customers for loss of supply due to severe weather is to increase from £700 to £2,000, a change of more than double.

5. **Cross-sector asset failure cascades:** in the current version of CReDo, cascade modelling was performed for all assets. However only failures from electricity assets can cause cascaded failures to water and telecommunication assets if they require power to function, but not from water to telecommunication and electricity assets, or from telecommunication to water and electricity assets.

6. **Pilot-to-national scaling factors:** identifying suitable scaling factors can be a challenge as multiple variables are at play: different asset owners have different sizes of asset sets, propensity for cascades, upstream/downstream dependencies, dependencies on different networks etc. Pilot areas have differing population profiles, population densities, combinations of commercial and residential utilities customers, flooding susceptibility etc. Regional roll-out strategies may accommodate different regions, scales, pace, members and use cases, all of which render a simple scaling factor from pilot to national subject to significant sensitivities – thus the benefits are estimated to fall within a potential range at this stage of development.

Mitigations

The first two challenges above prevent a view of real-word "Business As Usual" base case to compare the CreDo option against. Thus, the appraisal uses some assumptions (also referenced in section 3.1.1 "Options") to construct a proxy base case:

- **Investment budgets are derived from CReDo's asset criticality rankings –** as each incremental asset investment has a unique ratio of benefits to cost, the model finds the optimal budget in order to maximise Net Present Value of investments.
- **Asset owner investment strategies follow the decision models outlined in section 3.1.1 "Options" above.** In the Counterfactual this involves a blanket investment strategy across all assets, and in the CReDo Intervention option this involves prioritised investment in assets based on the asset criticality rankings.

The third, fourth and fifth challenges above result in the modelled benefits likely underrepresenting the total economic benefits of CReDo.

The sixth challenge above results in highly indicative pilot-scale-to-national scaling factors being considered at this exploratory stage of the strategic outline case:

1. **Population at significant risk of flooding –** modelling the population identified as at risk of flooding in the pilot area (north of Norfolk, 9.5% of population based on existing reports) in proportion to the population identified as at risk of flooding in the UK. Some challenges exist: available data on population at risk of flooding at the Norfolk scale and the UK scale refer to different probabilities of flood (1-in-75 year and 1-in-200 year respectively) and so were adjusted using the ratio of properties at risk of 1-in-200-year and 1-in-75-year floods in England and Wales, as a proxy. This gives a scaling factor of approximately 112.
2. **Population at significant risk of flooding (conservative) –** the same assumptions as above, but also using the Phase 1 assumption that 100% of the population in the pilot area were at risk of flooding. This gives a more conservative scaling factor of approximately 11.

These pilot-to-national scaling factors are thus exploratory

CRITICAL SUCCESS FACTORS

Critical Success Factors (CSFs) are the attributes that a proposal must have if it is to achieve successful delivery of its objectives.

For CReDo, two project-specific factors are included in line with its objectives (Climate Resilience and Data Sharing), in addition to several standard CSFs:

Critical Success Factors Evaluation of each option by...	
Strategic fit and meets business needs	• alignment with spending objectives, business needs & service requirements • holistic fit and synergy with other strategies, programmes and projects
Potential value for money	• ability to optimise social value (social, economic, environmental costs, benefits and risk)
Supplier capacity and capability	• capacity and skills of the market to deliver • appeal of the option to the supply side
Potential affordability	• availability and accessibility of funds
Potential achievability	• likelihood of delivery • alignment with skills to deliver
Influence on climate resilience	• extent can enable increase in infrastructure resilience, adaptation and mitigation
Influence on cross-sector data sharing	• extent can enable increase in secure data sharing across sectors, in a principled and scalable way • extent can develop a tangible working example of the National Digital Twin

Table 2. Critical Success Factors for CreDo

Not favourable Satisfactory Favourable

Critical Success Factors	Do Nothing	Blanket Investment Low-Mid Budget (Counterfactual)	Connected Digital Twin CReDo (Intervention)
Strategic fit and meets business needs	○	○	●
Potential value for money	○	○	◑
Supplier capacity and capability	○	●	●
Potential affordability	○	●	◑
Potential achievability	○	●	●
Influence on climate resilience	○	○	●
Influence on cross-sector data sharing	○	○	◑

Table 3. High level assessment of the options against the Critical Success Factors

Table 3 above illustrates an initial pass of how the CReDo Intervention and Counterfactual compare against the Critical Success Factors, based on project team insights and stakeholder interviews with asset owners and other public bodies. In summary, a connected digital twin (CreDo) is expected to score favourably against the strategic needs of asset owners in responding to climate-related resilience challenges; and likewise for the ability of the market to deliver and achieve its objectives.

Areas where benefits may score as satisfactory include potential value for money at pilot stage (but favourably at national scale – note the commentary in the appraisal below on benefits at pilot VS national scale); affordability (recognising a next step of CReDo is to solidify a revenue model that fits the regulated sectors' investment mechanisms) and influence on cross-sector data-sharing (recognising that CReDo is expected to enable cross-sector data sharing for its use cases and in its targeted sectors, but without claiming wider data benefits that are challenging to directly quantify or establish causality). See appraisal sections on the following page for more details.

APPRAISAL FINDINGS

Cost-effectiveness of resilience measures

As noted in section 3.1.4 "Model limitations", there are modelling challenges in obtaining a reliable view of Business As Usual resilience investment budgets that match the geographical boundaries of the pilot area and the functional boundaries of the use case (flooding only). Thus, in order to compare the CReDo Intervention option and the Counterfactual on a like-for-like basis, the same resilience investment budget is assumed in both options and the expected benefits compared under the decision models of each option. This budget is based on CReDo prioritising assets for investment based on their criticality rankings and comparing the expected benefits and costs of each intervention to arrive at an optimised budget constraint, i.e. the budget that will maximise the Net Present Value of investments based on a holistic, cross-sector understanding of asset dependencies. This same optimised budget can then be applied according to the different decision models in each option and scaled to national (UK) scale for indicative ballpark estimates.

The results in Table 4 show the results for the 2 scaling factors described in section 3.1.4.2 "Mitigations":

- **by population at significant risk of flooding (conservative)**
  At the more conservative end, the results show the Counterfactual decision model achieving benefits of £2.8m for the optimised resilience budget of £9.3m across all three asset owners, assuming investment costs scale in line with benefits.

  In comparison, the connected digital twin (CReDo) option applies the same budget to achieve £51m in benefits and a Net Present Value of £42m. This is a net difference in expected benefits of over £48m, giving CReDo a higher Benefit Cost Ratio of above 5 compared to Counterfactual's of less than 1.

- **by population at significant risk of flooding**
  At the higher end, the results show the Counterfactual decision model achieving benefits of £29.5m for the optimised resilience budget of £98m across all three asset owners, assuming investment costs scale in line with benefits. In comparison, the connected digital twin (CReDo) option applies the same budget to achieve £538m in benefits and a Net Present Value of £440m. This is a net difference in expected benefits of over £508m, with the same CReDo Benefit Cost Ratio of above 5 compared to Counterfactual's of less than 1.

Caveat: given the negative Net Present Value modelled in the Counterfactual option, it is unlikely that this is a realistic Business As Usual option in terms of investment strategy and budget within UK infrastructure networks. More work may be needed in future phases to define realistic BAU options as a baseline. Until then, the CReDo option alone demonstrates more than £508m in Net Present Value, with over £5 of modelled economic benefits for every £1 invested in asset resilience.

	Blanket Investment Low-Mid Budget (Counterfactual)	Connected Digital Twin CReDo (Intervention)	Net benefits (Intervention less Counterfactual)
National scale - scaling by population at risk of flood (conservative)			
Benefits	£2,797,000	£51,045,000	£48,248,000
Costs (asset investment)	£9,298,000	£9,298,000	£0
Net Present Value	**(£6,501,000)**	£41,747,000	£48,248,000
Benefit Cost Ratio	0.3	5.5	NA
National scale - scaling by population at risk of flood			
Benefits	£29,490,000	£538,191,000	£508,701,000
Costs (asset investment)	£98,033,000	£98,033,000	£0
Net Present Value	**(£68,543,000)**	£440,158,000	£508,701,000
Benefit Cost Ratio	0.3	5.5	NA

Table 4. Comparison of the cost effectiveness of resilience measures in the Counterfactual and CReDo options

Of note is the related insight that the Benefit Cost Ratio under the CReDo option varies greatly between asset owners – ranging from approximately 3 for one asset owner to over 19 for another (more than £19 in benefits for every £1 invested in asset resilience). This is based on an initial simple view of benefits for each asset owner against investment costs for each asset owner before any reallocation of costs is done. Such reallocation may be a realistic requirement of real-life cross-sector investment negotiations.

In future phases, work to address the challenges noted in 3.1.4 “Model limitations” (regarding asset failure cascades being modelled only from electricity distribution to other networks and not vice versa) may reveal different asset-owner-specific BCRs, as additional cross-sector cascade pathways can be identified.

Cost-effectiveness of CReDo

Whilst the above analysis considered the benefits and costs relating to asset resilience investments, the analysis below considers the cost of developing and maintaining CReDo. N.B. in order to restrict analysis to CReDo costs in the below analysis, the costs of asset resilience investments are treated separately by offsetting them against the expected benefits, per standard practice. Thus, costs of asset resilience investments are treated here as negative benefits.

Table 5 below compares CReDo’s expected benefits alongside its development and maintenance costs over the appraisal lifetime (to 2050). Estimates include optimism bias to account for the early stage of estimation and are discounted using HM Treasury’s standard Green Book Social Time Preference Rate (details in 3.1.3 “Model considerations”).

As can be seen, CReDo may generate a Net Present Value of between £34m and £432m depending on the scaling factor used – equivalent to a BCR of more than 5 when using a conservative scaling factor (number of asset owners) or more than 55 when using a higher scaling factor (population at significant risk of flooding).

	Blanket Investment Low-Mid Budget (Counterfactual)	Connected Digital Twin CReDo (Intervention)	Net benefits (Intervention less Counterfactual)
National scale - scaling by population at risk of flood (conservative)			
Benefits	£2,797,000	£51,045,000	£48,248,000
Benefits (asset investment as negative benefit)	**(£9,298,000)**	**(£9,298,000)**	£0
Total Benefits	**(£6,501,000)**	£41,747,000	£48,248,000
Costs (CReDo)	NA	£7,980,000	NA
Total Costs	NA	£7,980,000	NA
Net Present Value	NA	£33,767,000	NA
Benefit Cost Ratio	NA	5.2	NA
National scale - scaling by population at risk of flood			
Benefits	£29,490,000	£538,191,000	£508,701,000
Benefits (asset investment as negative benefit)	**(£98,033,000)**	**(£98,033,000)**	£0
Total Benefits	**(£68,553,000)**	£440,158,000	£508,701,000
Costs (asset investment)	NA	£7,980,000	NA
Total Costs	NA	£7,980,000	NA
Net Present Value	NA	£432,178,000	NA
Benefit Cost Ratio	NA	55.2	NA

Table 5. Comparison of benefits to CReDo costs

There is evidence that whilst available data estimates a BCR of between (approximately) 5 to 55, it could be higher due to the following considerations:

- **Understated benefits of foregone surplus:** CreDo's current benefits model can be expected to understate the actual benefits, for example additional foregone surplus such as the avoided losses to downstream commercial business activity from service failure, and additional externalities not currently monetised (see 3.1.4 "Model limitations").
- **Network effects:** relatedly, CreDo's pilot models three asset owners. As more networks are added, the number of asset interconnections will increase giving rise to "network effects": the more connections are introduced to a system, the more the benefits would be expected to rise in a non-linear way as different impact pathways become possible / identifiable.
- **Pilot location:** the costs and benefits of flooding-induced asset failure within the pilot area (within north of Norfolk) are not necessarily representative of the nation. As the pilot results inform the cost benefit analysis, any lower-than-average benefits will lead to benefits being understated at national scale – a pilot in a high population, high business density urban area such as London for example would return different benefits estimates than the north of Norfolk.
- **Foundation enabler:** the flooding use case explored in this Strategic Outline Case is the first use case intended out of a number of possible climate resilience use cases: extreme heat, wind, carbon accounting etc. The "flooding use case" CReDo is thus a first step which provides a foundation for other use cases to be built on asset owner data and criticality ranking algorithms. Whether they are cost-intensive additions or small cost add-ons will alter the overall BCR more or less positively for CReDo – costs for some such use cases are TBC in the near future.

In addition, BCRs are only able to capture quantitative benefits and by nature can not include the wider strategic and enabling benefits underpinning CReDo that are set out in section 2 "Strategic Case".

Some challenges with data availability are noted that prevent fuller comparison to the Counterfactual's development and maintenance costs. Whilst it was not within the scope of this phase to deep dive into asset owner tool costs, interviews revealed that current resilience decision-support tools are split across multiple systems, users and manual processes and with varying levels of coverage. Thus, a view of "Business As Usual" costs was not readily definable to the same geographic boundaries as the pilot area, or the same functional boundaries as the pilot use cases (flooding only). In future phases of CReDo, more detailed modelling of BAU costs across different assets owners may be performed to enable such comparison.

Cash-releasing benefits

The benefits of the avoided Total Economic Cost set out in the tables above include cash-releasing benefits for the asset owners.

These can be seen in Table 6 on the opposite page (the figures show the net difference between the CreDo Intervention and Counterfactual options). Cash-releasing benefits reduce actual expenditure, thus directly enabling budgets to be reduced or the spend reallocated elsewhere.

Business Costs and Regulatory Costs are both treated as cash-releasing because they involve direct expenditure by the asset owners. Regulatory costs (provided by the CReDo model via the appraisal methodology set out by Frontier Economics in Phase 2) are not included in Total Economic Costs because they largely attempt to proxy lost consumer surplus and would be double counted if included. However, they do give a more direct and measurable view of private costs to asset owners and thus are recognised here when totalling the expected cash-releasing benefits.

It can be seen from Table 6 that the cash-releasing benefits across all asset owners total at approximately £49m-£520m. The lost economic surplus for consumers is approximately £7m-£73m. Although not treated as cash-releasing in this analysis (because they are used mainly as proxy values for business planning), CReDo also expects to achieve in the region of £300k-£3m worth of fewer externalities. In the current model, externalities mainly pertain to pollution, compliance and sewage incidents within water networks and thus may also come with avoided reputational costs depending on the type of externality.

Under the highest scaling factor, lost economic surplus and externalities together form approximately £76m of the Total Economic Cost of £509m. This is approximately 15% - the public interest nature of CReDo's externality and consumer surplus benefits suggests the value of exploring whether public sector funding can support CReDo's initial development and / or market operation. This may be explored in future phases of CReDo: see 5.2 "Funding or financing mechanisms" in the Financial Case, and companion document Developing CReDo from Demonstrator to a Market-Ready Tool.

N.B. these figures and other net difference between the CReDo Intervention and the Counterfactual depend on a realistic Business As Usual which may be determined in future phases, as changes here will alter the expected net benefits. As such all figures are high level and indicative only at this strategic stage.

	Cash releasing?	Blanket Investment Low-Mid Budget (Counterfactual)	Connected Digital Twin CReDo (Intervention)	Net Benefits (Intervention less Counterfactual)
National scale - scaling by population at risk of flood (conservative)				
Total Economic Cost		**£2,797,000**	**£51,045,000**	**£48,248,000**
Business costs	Y	£2,209,000	£43,227,000	£41,018,000
Externalities		£18,000	£324,000	£306,000
Lost economic		£569,000	£7,494,000	£6,925,000
Other cash releasing		**£672,000**	**£8,986,000**	**£8,314,000**
Regulatory costs	Y	£672,000	£8,986,000	£8,314,000
Total cash releasing		**£2,881,000**	**£52,213,000**	**£49,322,000**
National scale - scaling by population at risk of flooding				
Total Economic Cost		**£29,490,000**	**£538,191,000**	**£508,701,000**
Business costs	Y	£23,296,000	£455,764,000	£431,468,000
Externalities		£191,000	£3,414,000	£3,223,000
Lost economic		£6,003,000	£79,013,000	£73,010,000
Other cash releasing		**£7,090,000**	**£94,741,000**	**£87,651,000**
Regulatory costs	Y	£7,090,000	£97,741,000	£87,651,000
Total cash releasing		**£30,386,000**	**£550,505,000**	**£520,119,000**

Table 5. Comparison of cash-releasing benefits – the values in the table show the net difference in benefits between CreDo Intervention and Counterfactual options

SENSITIVITY ANALYSIS

Options

To better compare the Intervention (CReDo) and the Counterfactual (Blanket Investment, Low-Mid Budget) options, different inputs can be considered in terms of the decision models. This gives alternative comparison options as below:

- **Blanket Investment, High Budget:** The decision model for making resilience investments is for asset owners to make blanket investment across all assets with no prioritisation considered. Where alternative measures are available for an individual asset, they invest on the highest cost measure.
- **Siloed Digital Twin:** A within-network only digital twin that any asset owner may have – this provides specific knowledge of asset criticality within the asset owner's own network, but no insight into cross-sector asset criticality or interconnections. The decision model for making resilience investments is to assess the criticality rankings of the assets in their individual network and make prioritised investment decisions accordingly – the Benefit Cost Ratios for each possible investment are ranked and prioritised.

These additions are considered alongside the main appraisal's options in Figure 3. Figures are considered for the pilot area based on data directly in the CReDo model. In this view, budget constraints are removed and each option assessed according to the cumulative investments that would be made under its unique decision model. For many assets, alternative investment options are available and the resultant costs can be compared with expected benefits to produce Cost Benefit Ratio for each asset investment. These Cost Benefit Ratios can be ranked in order of magnitude, and the ranking will be different according to the differing views of cost and benefits under each option and its decision model for investment.

The resultant rankings then indicate the unique set of prioritisations and investment pathways under each option. In Figure 1, the curves demonstrate different total benefits available within the pilot area at different budget sizes, with each new asset investment adding to the cumulative implementation cost on the x-axis and the corresponding cumulative total benefits shown on the y-axis.

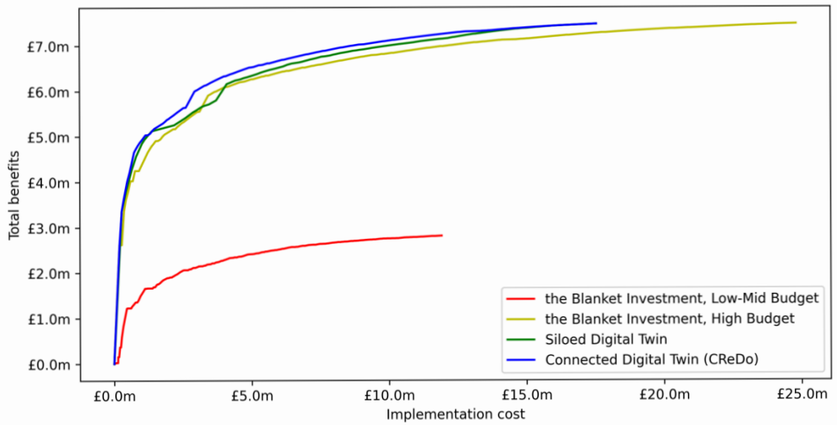

Figure 3. A comparison of the total benefits and costs of the four options

In general the curves see diminishing returns on investment as the assets with higher BCRs are invested in first whilst the later assets investments have steadily lower and lower BCRs. Of note:

- The Blanket Investment, Low-Mid Budget option is the least cost effective, making sub-optimal investment selections that bring significantly lower benefits that the other options.
- The Blanket Investment, High Budget option; Siloed Digital Twin; and Connected Digital Twin (CReDo) options all eventually reach the same level of benefits (£7.5m) but have varying levels of cost-efficiency. The Siloed Digital Twin and Connected Digital Twin (CReDo) options both require investment of £17.5m to unlock those benefits, whereas the Blanket Investment, High Budget option requires a budget of approximately £24.8m (41% additional budget for the same benefits). The assumptions underlying the chart (that asset owners will invest in every possible asset and face no budget constraints) is not considered realistic because under these assumptions asset owners would keep investing in every asset even past the point where the Net Present Value become negative, and so the NPVs or BCRs of the total investment and benefits are not relevant. More important in this analysis is the relative overall cost-effectiveness of the overall investment pathways, as shown in the figure.

Figure 4 gives a closer view of how the investment pathways diverge – the Blanket Investment, High Budget; Siloed Digital Twin; and Connected Digital Twin begin with the same investments and similar total costs and benefits. At around the £2.5m benefits mark, the Blanket Investment, High Budget (light green line) begins to make sub-optimal investments, due to its lack of insight on failure cascades. At around the £3.5m benefits mark, the Siloed Digital Twin (dark green line) begins to make sub-optimal investments, due to its view of asset failure cascades being limited to one asset network only, and missing the holistic, cross-sector view. At this point the Connected Digital Twin (CReDo) maintains the highest benefits to costs ratio on an ongoing basis, for any chosen level of investment.

The difference in benefits between a Connected Digital Twin (CReDo) and the other options would be expected to increase as additional asset owners are added to the model (network effects), additional benefits are modelled and additional failure cascade pathways are modelled. At about the £4m implementation cost mark, the benefits gap between the top three options closes as opportunities for investment align regardless of the decision model used.

Cost-effectiveness of CReDo, the difference in benefits between a Connected Digital Twin (CReDo) and the other options would be expected to increase as additional asset owners are added to the model (network effects), additional benefits are modelled and additional failure cascade pathways are modelled. At about the £4m implementation cost mark, the benefits gap between the top three options closes as opportunities for investment align regardless of the decision model used.

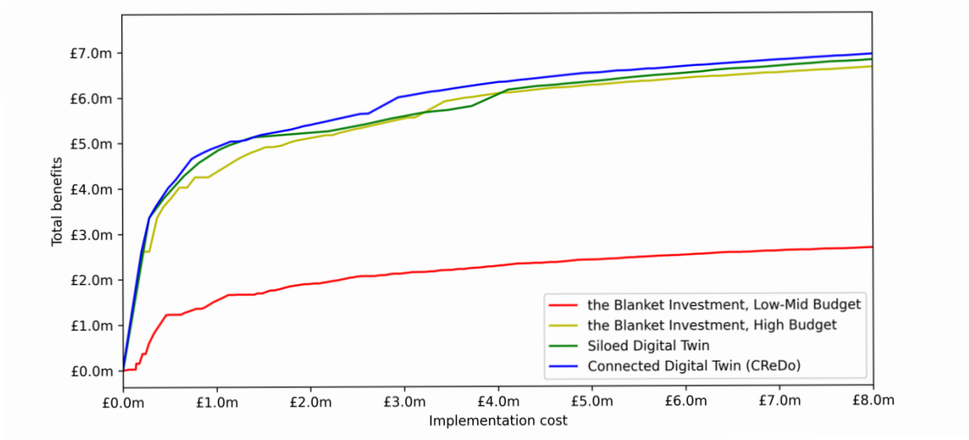

Figure 4. A subset view of Figure 1, detailed how total benefits and costs diverge across the four options

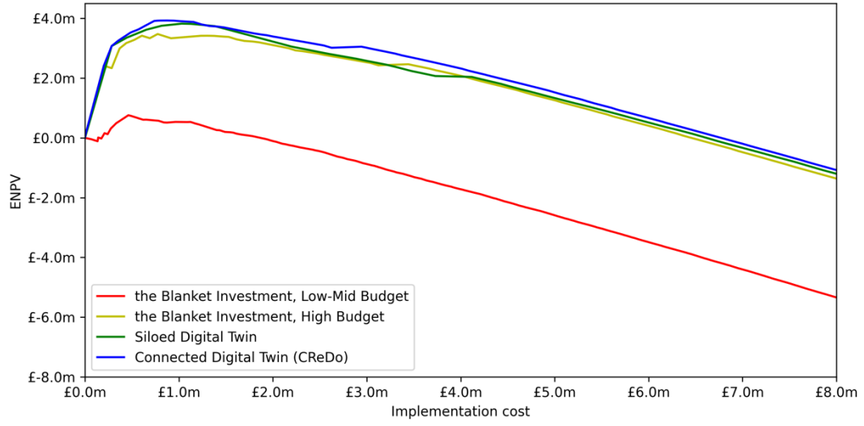

Figure 5. The expected Net Present Values at different investment levels under each scenario.

Applying the same optimised budget constraint as considered in section 3.3.1 “Cost-effectiveness of resilience measures” above, the four options would have respective BCRs of:

- Blank Investment, Low-to-Mid Budget (Counterfactual): 0.3
- Blank Investment, High Budget: 0.4
- Siloed Digital Twin: 5.3
- Connected Digital Twin CReDo (Intervention): 5.5

Neither of the blanket investment strategies have BCRs comparable to those of the digital twins. The Siloed Digital Twin option has a lower BCR than the Connected Digital Twin (CReDo) option, due to being unable to see truly holistic, cross-sector asset interdependencies and failure cascades. The difference is relatively small at the pilot prototype stage, but as stated above, the difference in benefits would be expected to increase as additional asset owners are added to the model (network effects), additional benefits are modelled and additional failure cascade pathways are modelled.

SUMMARY OF BENEFITS

Cost-effectiveness of resilience measures

Under the analysis, the Benefit Cost Ratio of asset resilience investments is above 5 under the CReDo option in comparison to approximately 0.3 under the assumed Counterfactual of Blanket Investment, Low-Mid Budget, with a difference in ballpark Net Present Value of over £48m-£508m at national scale, based on the conservative and higher scaling factors respectively.

The Benefit Cost Ratio under the CReDo option varies between asset owners – ranging from approximately 3 for one asset owner to over 19 for another (more than £19 in benefits for every £1 invested in asset resilience). This is based on an initial simple view of benefits for each asset owner against investment costs for each asset owner before any reallocation of costs is done. Such reallocation may be a realistic requirement of real-life cross-sector investment negotiations.

Cost-effectiveness of CReDo

When considering scaling from pilot scale to national (UK) scale, costs may scale at a factor of approximately 2 (due to the nature of digital technology and code being highly scalable) whilst benefits may scale at a higher rate such as between approximately 112 (based on proportion of the population at significant risk of flooding) or a more conservative figure of approximately 11 (based on more conservative estimates of the proportion of the population at significant risk of flooding).

As such, CReDo may generate at national scale a Net Present Value of between £34m and £432m depending on the scaling factor used – equivalent to a BCR of more than 5 when using a conservative scaling factor or more than 55 when using a higher scaling factor.

Cash-releasing benefits

The expected cash-releasing benefits across all asset owners total at approximately £49m to £520m cash-releasing benefits, and between £7m and £73m of avoided lost economic surplus.

Sensitivity Analysis

The results are highly sensitive to the assumptions used in the Counterfactual, against which the CReDo Intervention is compared. When two other options are introduced (Blanket Investment, High Budget; and Siloed Digital Twin), it can be seen the asset investment strategies recommended by digital twins remain the most cost effective. Neither of the blanket investment strategies have BCRs comparable to those of the digital twins.

The Siloed Digital Twin option has a slightly lower BCR than the Connected Digital Twin (CReDo) option (both above 5), due to being unable to see truly holistic, cross-sector asset interdependencies and failure cascades. The difference is relatively small at this prototype stage, but as stated above, the difference in benefits would be expected to increase as additional asset owners are added to the model (network effects), additional benefits are modelled and additional failure cascade pathways are modelled.

Limitations

N.B. the figures and other net differences presented between the CReDo Intervention and the Counterfactual depend on a realistic Business As Usual which may be determined in future phases, as changes here will alter the expected net benefits. As such all figures are high level and indicative only at this strategic stage.

Other non-monetisable benefits

Stakeholder workshops and interviews revealed additional benefits are expected beyond the quantified modelling assessed above, including increased service quality and cost reduction, protection of vulnerable sites and groups and innovation spillovers. Some monetisable benefits are not currently included under the Frontier Economics Phase 2 methodology, for example additional environmental externalities as referenced in their methodology report.

Other non-monetisable benefits

Asset owners already know who their vulnerable customers are, for example hospitals, sensitive national sites etc, but may still find themselves unaware of the potential cross-sector cascades that could cause services to fail to these important groups. This can include strategically placed military bases, highly water intensive industrial users such as breweries, customers with different language requirements and faith groups, etc.

"[For] a very critical site of ours, we thought we had two supplies to the site - but if you track back through the power supply network, back through the nodes in that supply, we found they had ONE common power node - if it failed, both of our critical supplies would go out.

It was one of our most critical sites, caused us to invest in our infrastructure - we had to invest to mitigate our risk."

Asset Owner, water sector)

Improved collaboration across other sectors, due to the value of secure data sharing

By demonstrating a truly cross-sector initiative of data sharing, complete with building trust and overcoming of any legal or sensitivity issues, CReDo hopes to encourage other organisations and sectors to see that collaboration can be done. There are varying orders of complexity: public sector organisations, especially non-competing ones such as water networks, may find a primary objective around data to be good data stewardship, maintaining the required privacy, security and sensitivity of data. Organisations directly competing with their market, however, face additional commercial complexity on the levels of data that can be shared, under what circumstances and with whom. By demonstrating that sectors can collaborate and share data, CReDo may add a useful case study as it matures its data sharing from bespoke manual methods to APIs and role-based access levels etc.

"We (networks) don't understand each other - we work in parallel. There will come a time when we need to work together - it is in everyone's interests. A digital twin is the missing piece of the jigsaw."

Asset Owner, water sector)

"We're gaining a gradual awareness that people outside our sector have better ideas than we have. We need to collaborate - we can't keep working in a bubble."

Asset Owner, water sector)

RISK ASSESSMENT

Risks have been identified for the scaling of CReDo that could affect the expected benefits. Mitigations have been applied and costs allocated where reasonable for risk mitigation. These include:

Description	Mitigation
Challenges in availability and readiness of existing climate modelling data	• CReDo's data architecture is designed to leverage existing and new data
Challenges in the accuracy of predictions in existing climate models	• CReDo may use an ensemble of models – and even ensembles within one model – and take average of the results
Collaborative data exploration license is not scalable	• Accession process allows new asset owners to join, but limitations remain around data sharing by competitive asset owners
Collaborative data exploration license is restrictive	• Future phases of the project may explore opening from data exploration licenses to APIs (Application Programming Interfaces) and the use of pre-set access levels
Malicious misuse of sensitive asset data by 3rd parties	• Cybersecurity is an important consideration for future development of CReDo. Current technical plans include for example data being managed securely via APIs with pre-set access levels for users
Data infrastructure maturity / readiness of new asset owners	• Assess the infrastructure and data maturity / readiness of potential asset owners looking to join CReDo. CReDo may use data transformation agents to convert different data formats
Limited buy-in from industry / Asset Owners	• Stakeholder engagement on the unique value proposition of CReDo, its cross-sector insights
Limited buy in from government / regulators	• Continued engagement with regulators, demonstrating the value of being view-only users of the system
Regulatory restrictions on cross-sector asset investment	• Some challenges in the incentives and price review structures with regards to cross-sector investing may need to be accepted ed as beyond the short term control of this project
Password sharing – if Users re-use or share passwords then license revenues may be reduced	• Identify users by mac address (a mac address is a unique alphanumeric identifier, each individual electronic device on a network has such a unique code)
Asset owners cancelling subscription immediately after they have gathered / downloaded all the insights they need for the next 2-5 years	• Data that users would be able to download would only be accurate in the very short term, and become obsolete / misleading once new assets were installed or new asset data ingested
Asset owners' existing systems and tools seen more / as mature as CReDo	• This may be true for an asset owners' insights into their own internal network, but into their own internal network only – CReDo will be more advanced in terms of cross-sector insights, and this is a unique offering not matched by asset owners' current systems
Computing power required for processing the number of interconnections (performance / availability)	• TBC if the processing is done in the cloud – whether it is relatively easy to choose a higher service level when / if needed
Potential unreasonable expense of data storage	• TBC if resolved through decentralised data storage. CReDo may need a catalogue of climate events that can be loaded into scenarios

Table 7. Summary view of risks that may affect CReDo's ability to drive economic and social benefits

COMMERCIAL CASE

This section considers supplier capability and risk appetite in the market to deliver CReDo.

Procurement strategy and route

Until deeper design considerations are ready, and a go-to-market route reached, the commercial case is of limited applicability at this stage: procurement is not relevant to CReDo currently.

Rather, a key question is how it can be funded and drive revenues to be commercially sustainable, either through central or local government use, regulator endorsement / provision, asset owner subscription or varying models and combinations thereof. This is considered in more detail in the Financial Case below.

Skills required in the market

As a nascent digital twin, CReDo does rely on some skills being available within the market of the consortium, depending how the project evolves and key elements on what happens in-house versus in the market (for example, questions over whether data storage is local or cloud-based, etc). Based on sessions with the CReDo team and cost planning these may include, but are not limited to:

- Compute hosting
- climate modelling
- cyber security
- data analysis
- data and cyber infrastructure development
- data assessment, ontology development, pipeline
- digital twin engineering
- distributed data sharing
- communication, engagement and dissemination
- flood data / modelling
- full stack developers
- Python sandpit modelling
- resilience metrics
- user experience and interface

With the possible exception of some advanced skills within cyber security, skills are deemed by the project team to exist readily in the project partners and / or in the UK market as a backup if needed.

Cybersecurity is an important topic for a digital twin such as CReDo, hosting data from multiple organisations and occasionally of a sensitive nature. External consultants holding expertise in the market may be consulted and engaged, as well as the use of distributed architecture are actions that will ensure CReDo is robustly developing in this area.

Outline risk allocation

Based on the risks identified in Table 7 above, some of these risks may be transferred to specific partners (or contracted organisations), according to how responsibilities are shaped going forward in future phases (TBC).

Risks on asset owner maturity / readiness are best placed with those able to manage those risks, i.e., the asset owner. If there is no pre-existing standard or agreement on what “good” climate modelling looks like in each scenario, then data wrangling will be iterative in nature as agreement is reached. Different networks / partners may have different preferences on the desired level of perfection vs practicality. CReDo is designed to easily leverage (existing and new) climate data, but generating and processing new datasets into a readily usable form is not envisioned to be within CReDo core scope. Instead, the risk affects potential new networks if they have a dependency on usable climate data. The costs may therefore fall within the costs of their feasibility assessments, as they make enhancements or upgrades to their infrastructure in order to be CReDo-ready.

Alternatively, regulators may decide that the wider industry benefits of providing (or stimulating the market to provide) high quality datasets is worth funding. This climate model risk could therefore be a cost that:

- asset owners need to pay for in addition to the license price, OR
- regulators fund via their Strategic Innovation Funds or other funding mechanisms

FINANCIAL CASE

This section sets out considerations on funding sources for CReDo and the main cost drivers of its development and maintenance.

Capital and revenue requirements

A CReDo digital twin is envisaged to require core development and maintenance phases to take it from prototype demonstrator to functioning digital twin. Those activities generally fit under cost types that are upfront development or ongoing support and maintenance, and within those fixed, variable, semi-variable or step costs. Some areas are known to the project team as primarily suitable for going to market (cyber security, penetration testing etc) whilst others are expertise and skillsets held by the consortium.

See Table 8 below for an indicative view of the cost drivers for CreDo at national scale, presented to the nearest £10k for a typical year in 2023 prices. These figures include 20% VAT and optimism bias (see section 3.1.3 "Model considerations" above for specifics).

Cost driver	Development Cost Per Year - National Scale	Maintenance Cost Per Year- National Scale
Project, Delivery and Technical Management	£270,000	£20,000
Use Case Development and User Workshops	£450,000	£60,000
Data Discovery, Gathering and Processing	£1,010,000	£80,000
Data Science and Infrastructure Modelling	£260,000	£20,000
Digital Twin Engineering and Software Development	£670,000	£90,000
Data Hosting, Data Infrastructure and Cyber Security	£320,000	£40,000
Strategy, Evaluation and Business Case	£20,000	£3,000
Engagement and Dissemination	£280,000	£80,000
Total	**£3,280,000**	**£393,000**

Table 8. High level view of cost drivers for the development and maintenance phases of CReDo at national scale. Costs are presented as high level to nearest £10k.

Phase duration (number of years)	MVP	Enhanced version
Development phase	1	5
Maintenance phase	25	21
Total	**26**	**26**

Table 9. High level phase durations for Development and Maintenance phases

Minimum Viable Product (MVP)

It is expected that a Minimum Viable Product (MVP) version of CReDo could therefore require approximately:

- **£3.3m to develop CReDo as an MVP in the short term –** 1 year of development costs (in 2023 prices due to 1 year's development in 2023, or if that 1 year of development began in 2024 then £3.4m in 2024 prices).
- **£0.4m (2023 prices) per year for recurring maintenance costs.** Section 5.2 "Funding or financing mechanisms" below explores revenue model options to sustain the running and maintenance of CReDo in the longer run.

Approximately £17m costs to 2050 (nominal) could therefore be expected, including 20% VAT, optimism bias (see section 3.1.3 "Model considerations" above for specifics), and inflation over the appraisal period. This MVP version is also the version considered in the Economic Case above because it is what most closely matches the current CReDo benefits model.

Enhanced version

Expanding to an enhanced version (additional features, Software-as-a-Service etc) is expected to require 5 years of development phase and 21 years of the maintenance phase. Making the same adjustments as described directly above, this would require:

- **£17.3m (nominal)** to develop CReDo as an enhanced version in the short term – 5 years of development costs.
- **£390,000 (2023 prices) per year for recurring maintenance costs.** Section 5.2 "Funding or financing mechanisms" below explores revenue model options to sustain the running and maintenance of CReDo in the longer run.

Approximately £29m costs to 2050 (nominal) could therefore be expected, including 20% VAT, optimism bias (see section 3.1.3 "Model considerations" above for specifics), and inflation over the appraisal period.

The section below considers revenue models to sustain the running and maintenance of CReDo in the longer run.

Funding or financing mechanisms

Overall affordability and funding

This section considers revenue models to sustain the running and maintenance of CReDo in the longer run. A key challenge for CReDo is that whilst there is a clear set of benefits, they are fragmented across:

- Beneficiaries who are not users (consumers and businesses who receive stable service quality, for example).
- Users who may benefit in ways disproportionate to their own investment (e.g., if an upstream asset owner invests in resilience measures but it's other networks who receive all the benefits, are the incentives aligned).
- Users who do not have mechanisms for cross-sector investment, due to the structure of how funding, objectives and incentives are agreed in regulated sector Price Reviews and Controls.
- Different levels, remits and geographical boundaries of organisations, from local utilities to national governmental bodies, each with slightly different needs and relationship to each other in terms of collaboration/competitiveness, data sharing and reporting.

Therefore, a key challenge facing CReDo's future is how to construct a commercially viable revenue model that not only delivers sufficient value to each participant but, is acceptable and realistic in terms of available budgets and spending objectives of the different organisation types who may use CReDo.

Interviews were conducted with stakeholders including asset owners and public bodies across water, electricity, telecommunications, and transport sectors to explore possible revenue models that can address the above.

Key findings are presented below by stakeholder group, before the section outlines and recommends specific revenue model options for CReDo and its stakeholders to consider going forward.

Government Authorities

- Tendency to operate on a principle of subsidiarity, i.e. the central or higher authority has a subsidiary function (performing only those tasks which cannot be performed on a more local level). While authorities have business continuity functions, lower agencies have their own as well.
- Authorities are unlikely to own or control any assets themselves (with the exception of assets such as local roads), but they are motivated to retain a "birds-eye view" of the infrastructure for functions such as security and international/operational response. Number of business continuity planners within authorities varies wildly, but primary research indicates that each authority has 10 to 20 planners (excluding civil servants from other departments) dedicated towards monitoring infrastructure resilience. Authorities are likely to at least want the capability to view the infrastructure nationally (rather than locally). If CReDo recorded all national-scale assets, this would make the service attractive to relevant authorities.
- Authorities are keen to develop an environment of outcome-based innovation for local agencies, so that they can develop their own solutions and so that the authorities will not be blamed if anything goes wrong.
- Authorities do not test for things that they are not responsible for; they do have teams that perform general risk analysis within domains that they are responsible for, but they stop whenever the analysis moves into areas that other public/private sector entities are responsible for.
- The main benefit of CReDo is generally perceived as being an opportunity for all authorities to consolidate data sets within a single source, thereby minimising the chances of work duplication and data conflicts.
- Cutting costs is a significant issue for government authorities, as departments have financial challenges. However, if a case can be made for resilience across government sectors, this will be a large benefit in marketing CReDo to authorities. Mitigating loss of life is a hugely persuasive topic for government.
- Government procurement of services follows a standard format; issue an ITT (Invitation To Tender) and receive a number of tenders. Each ITT has a set price that is non-negotiable, and each tender is assessed on both quality and price. Authorities contacted during primary research consider price to be more important than quality, with price being 60-70% of the selection criteria. For security reasons, procurements of these service types tend to be bespoke and not off-the-shelf.
- There is a possibility that CReDo could be used to apply layers on top of current system mapping and modelling processes, although government buyers of CReDo need to be convinced that the marginal benefit of doing this is sufficient to warrant the purchase over a multi-year period.
- Government authorities conduct continuous negotiations with all agencies on the settlements they receive from central authorities, and these settlements are reviewed every 3-5 years. If the agencies are being subsidised, then these payments will also involve the use of relevant Information Management Systems.

Regional Utilities

- While business continuity is increasingly becoming a prime concern for utility companies, few companies have developed specific departments that have been incorporated to fulfil the necessary research and analysis. However, there would be small number of personnel within the utility companies tasked with looking at business continuity as part of their roles to varying degrees.
- Depending on the overall size of the organisation, it is unlikely that there would be more than ten individuals solely dealing with business continuity on a regular basis. Larger organisations have developed teams that are focussing on different aspects of business continuity and climate resilience; these include small groups that are focussed to varying degrees on themes such as strategic planning, carbon neutrality, flood risk management and tactical event/emergency management. No organisation interviewed during this research had relevant personnel exceeding more than 25 in number, but other organisations may have more personnel related to climate resilience and/or business continuity.
- Utility companies interviewed have conducted various levels of business continuity analysis with varying levels of results. However, the need for this type of analysis has become more noticeable recently, given recent issues regarding 40-degree temperatures.
- Ongoing analysis has started, and plans are beginning to be developed with the intention of acting on research findings. For certain utilities, themes such as emergency power resilience are becoming more prominent. Larger companies have already taken steps to engage with service providers to mitigate any future events.
- The use of online services to support business continuity planning is difficult to accurately ascertain, as most organisations either use a wide variety of disparate services (both third-party and online) to fulfil their needs or have no discernible dependency on any online service at all. Specialised third-party consultancy firms have a track record of providing modelling services to several utility companies, and they are paid on a pre-project basis as & when they are tasked.
- Subscriptions to online services do not have a common trend as far as subscription models are concerned; the buyer adapts to whatever model is presented and to whatever value the service can provide. Subscribed services adopted by some organisations may be slightly chaotic, as multiple services sometimes have value that overlap each other. Current online services include Ovarro (which provides monitoring and control, analytics and SCADA solutions for critical assets and infrastructure) and Samotics (which creates products to solve the problem of unplanned downtime and energy waste for global industrial companies).
- One key element of the attractiveness of an online service is whether the underlying data of that service can be integrated into organisational capabilities developed internally and how effectively this can be done. This may involve the development of data standards.
- There has been no identifiable move to lobby any regulatory and/or government authority to pay for any online services. Some utility companies are experiencing financial difficulties which restricts their ability to adopt relevant services; economic constraints have dampened their willingness to pay for further services that may be expensive over the term of the subscriptions. Therefore, any understanding of any value proposition such as CReDo would have to be clear, and a certain level of cost/benefit analyses would have to be conducted. In general, financing for the service would not be a hurdle if it was the right tool with the right benefit.
- As far as the revenue model is concerned, the number of people involved in business continuity would lead to a preference for a user license model (the Netflix model) or a restricted capability model. Depending on the organisation's geographical focus, overall subscription flexibility is not an issue. Some organisations have the necessary budget for affordable services, but these are unlikely to be ad hoc purchases and would need to be planned for. As stated in interviews, some budgets for climate resilience/business continuity have been declared in the millions of pounds, but it is unclear as to how much of that budget will be redirected from direct MRO to software services

National Infrastructure Owners

- Much like regional utilities, national infrastructure asset owners have specific departments where business continuity and resilience are part of their responsibilities. The number of organisational personnel with business continuity and resilience in their portfolio of responsibilities can be as low as two, although other people with responsibilities for planning may be involved periodically. Infrastructure owners are usually regulated by organisations such as the National Protective Security Authority (NPSA), formerly known as the Centre for the Protection of National Infrastructure (CPNI).
- While the nature of the assessments conducted by internal resources tends to be unclear, there is a tendency for national infrastructure owners to rely on external support for the conducting of business continuity exercises such as planning and periodic reviews. According to primary research, these exercises have resulted in organisational changes that are considered to be broad but relatively shallow. However, activities of this nature are becoming more rigorous and standardised than they have been in the past 5-10 years. These activities are continuing to be subject to continuous improvement and has become subject to annual review. Analysis will continue to involve how disruptions in dependencies from other industry sectors affects the business, and the drive to continue this type of analysis has become part of day-to-day executive policies that extend far into the future.
- While external service providers continue to be used and the buyers have generally been happy with their service levels, the drive to reduce their involvement (other than providing impartial advice and some policy assurance) – while still retaining the option to employ their services in a more in-depth manner – is noticeable. Whether the reduction in the use of external providers can be compensated for by internal capabilities is unclear, as infrastructure owners have expressed a willingness to develop partnerships with contractors, consultant, cyber security specialists, system integrators, etc. but have not explicitly stated that these partnerships could provide a service like CReDo. These partnerships tend to be in the context of a wider service base that they provide to the customer.

Revenue Models

Subscription Types

Within this research, six revenue models were considered for CReDo:

- **Freemium**
  Customers are given partial or total access to “real world” or simulated data for a period so that they can experience the product first hand before they decide to purchase a subscription.
- **Flat rate/recurring/periodic**
  Customers regardless of size can purchase access to data with little to no restrictions on the number of users or data that they consume.
- **“Pay As You Go” (PAYG)**
  Customers only pay for the data that they consume and the service elements that they use.
- **Tiered**
  Customers can choose different data & functionality aspects of the service on a semi-permanent basis
- **User licenses**
  Customers can purchase access to data and functionality but restrict usage to a set number of people.
- **Value-based**
  Customer pricing models are set by an agreed-upon level of value that they can extract from the service.

Freemium

While this subscription model offers the greatest opportunity from a customer acquisition perspective, it has extremely limited efficacy for revenue generation. Unless detailed simulated data is included within the free trial that encompasses all elements of CReDo’s functionality, there is a risk that the trial will allow potential customers to extract all necessary data and forego any further subscription.

Flat rate/recurring/periodic

This option – all functionality and all data for one price over a predetermined period of time – offers the client the simplest and most predictable method of purchasing the service in a way that is easy to budget for. However, it makes little to no distinction between customers of varying sizes; this option maximises the possibility that smaller customers will be paying the same rate as larger customers.

Pay As You Go” (PAYG)

This option allows customers the option of consuming as much data and taking of advantage of as much functionality as is necessary for the requirements. This is a good option for new users who would like to test CReDo in its entirety with real-world data, but also allows users to control what data and functionality they use if they want to control costs. It will require developers of the service to incorporate relevant tracking capabilities to measure what data & functionality is used, when it is used and to what degree.

Tiered

The tiered system is where different aspects of the CReDo service is allowed/denied on a semi-permanent basis based on the chosen tier. While this option may appeal to potential users who can choose their best tier based on their unique requirements, it also reduces the opportunity to upsell functionality to existing customers, requires an increased level of service complexity caused by deeper levels of required functionality, and may result in confusion if the tiers are insufficiently customer-centric.

User Licenses

User licensing – or "per seat" licensing – is the option that is the most used method of licensing for a wide variety of different SaaS available today, and is consequently the most understandable for potential customers. It offers interested parties an a la carte experience when choosing their required levels of data and functionality and gives a set number of users all that they require. From a revenue perspective, this option is not clearly linked to any sense of value for the customer, and one user license may provide as much as value as ten user licenses, i.e. this may have the tendency of reducing revenue generation opportunities for the developer.

Value-based

This option establishes a service price based on the value that it can provide to the purchased. However, the service value is determined by the customer, so potentially complex negotiations would be required to ascertain service price.

Conclusion and Recommendation

While all the aforementioned options (except for the freemium model) offer potential clients a path to using CReDo based on their requirements, the optimum model that covers a significant proportion of the requirements highlighted by government authorities, regional utilities and national infrastructure is a combination of two models: user licensing and PAYG.

The user licensing element of this combination offers customers the opportunity to focus on providing relevant personnel with access to CReDo while allowing them to choose which data elements and functionality they need to undertake their business continuity work, which is ideal for both national infrastructure owners who require a broad (yet potentially shallow) understanding of external dependencies, and regional utilities who are geographically focussed but may require a relatively deeper overview of the dependencies in their region. This type of model is also in line with the low number of personnel who are either directly focussed on business continuity or who are involved in related roles daily.

Government authorities are also likely to appreciate the potential to reduce costs during normal oversight activities while retaining the option to dramatically increase data consumption, the number of licenses and additional functionality in times of crisis.

Commercial Models and Structures

The following research outlines the potential models that may be applied to the ownership of CReDo and highlights the advantages and disadvantages of each.

Government Authority

Definition: Any organisational entity that is entirely or strongly influenced by authorities connected to regional and/or national government. This includes governments, regulatory authorities or any public sector entity.

This model indicates that CReDo in its entirety is absorbed, owned and managed directly or indirectly by a government authority that supports, maintains and updates the system, and sells access to the system to interested parties.

While this model has probably the highest level of trust with regards to data integrity and security, it is unclear as to the potential further progress of the product, given that government has a mixed track record when it comes to software development. Along with the possibility of a considerable loss of operational focus on CReDo, overall subscription fee levels and future development of the system has the potential of becoming politically motivated rather than revenue oriented.

Private Sector

Definition: Any private sector entity that functions in non-governmental ownership that operates within regulatory frameworks established by authorities but does not generally require input and/or oversight from authorities for day-to-day operations.

This model involves transferring ownership of CReDo as a minimum viable product (MVP) to an established private sector organisation that is prepared to continue development of the system and sell subscriptions to the open market.

Along with the reasonable possibility of the system buyer continuing development of CReDo in order to recoup purchase costs, government funding for future development will become less of an issue (if at all). The initial investors in CReDo could also negotiate a sale price that covers all previous development costs.

However, in spite of CReDo being developed for the "public good", the system buyer would have the majority of control over fee levels and/or structures, thereby potentially limiting uptake by potential customers and may place barriers to uptake by regulators and/or specific sectors. There is also the relatively high possibility that preferential access to data will be reserved by the owner of the product, resulting in the buyer's competitors not being guaranteed to receive the data access that they pay for. It is also unclear how data integrity and security could be maintained without potentially intrusive oversight.

This model is a potentially workable solution if specific guidelines are in place, but care needs to be taken when selecting the correct administrator of CReDo. The concept of the "public good" will also need to be considered if a bidding war were to occur.

SME with Oversight

Definition: Similar to "Private Sector", but with meaningful input from both the public sector and external private sector stakeholders.

This model involves establishing a new corporate entity that continues to develop, maintain, support and enhance CReDo on an ongoing basis. Initial customers share the cost of establishing the structure, get a seat on an "operational/advisory board" and have a say in all aspects of the service's future. Government authorities continue to have oversight relating to system integrity, data security and protecting the concept of the "public good".

Of all the models, this one will be most able to reflect the needs of the target markets, e.g. fee levels and functionality. As well as being nimbler in future development plans and promoting fairness among relevant industry sector participants to increase uptake, fees being paid into an independent organisation is most likely to negate the need for significant additional government funding. Possibilities to sell the CReDo framework in the international market may appear, and the opportunity to sell a more developed version of CReDo to the private sector may generate significant profits.

However, spinning CReDo off into an SME currently requires an unknown level of seed capital. Along with potential difficulties in convincing private sector entities both investing in the new company and involving themselves at board level, conflicts may arise in customers' opinions on the future of CReDo.

In general, this model ameliorates most of the hurdles of CReDo development and funding and takes advantage of most of the future revenue benefits. Flexibility, openness and transparency for the end-user is likely to be a big plus for future marketing activities.

Public/Private Partnerships (PPPs)

Definition: Joint ownership and operations between public sector authorities and private sector investors.

This model involves CReDo remaining within the purview and control of CPC or another semi-public body, while private sector entities contribute a large share of the further development costs with the intention of recouping these costs from future commercial activities.

This model also retains a healthy level of market adaptability while still allowing authoritative oversight (similar to SME with Oversight) but with the government authorities retaining the majority of control), i.e. keeping a private sector mindset with a continuing focus on the "public good".

However, based on initial feedback from both government authorities and internal CPC discussions, this model may not be the best fit for a service such as CReDo. PPPs are usually considered suitable structures for large infrastructure projects however CReDo does not fall into this category.

Open Source

Definition: The free distribution of CReDo software and its source code, making it available for use, modification, and distribution with its original rights.

While this model will most likely result in the widest distribution of CReDo both nationally and internationally, it fails to retain the main advantage of the system, namely a coordinated framework that facilitates sharing of data from different industry sectors. In addition, it offers little to no future revenue opportunities; in essence, CReDo will be distributed openly and will eventually fragment (similar to the distribution of Linux operating systems).

In short, this model may cause the "public good" ethos of CReDo to become diluted, while offering no meaningful prospect of earning back funds spent on the project.

Conclusion and Recommendation

While active steps are currently being taken to engage with the market and a range of key stakeholders to ascertain the feasibility of the different options and their potential combinations, CPC have not finalised the optimum commercial/revenue model and are simply putting forward recommendations for the consideration of interested parties.

Except for Open Source, each of the commercial models incorporate some of the necessary elements that would be acceptable to sub-sections of any potential market and/or the continuing development of CReDo as a whole: trustworthiness, market adaptability and understanding, reasonable costs, and future development prospects.

The SME with oversight commercial model is most likely the only option that will be able to fulfil all positive criteria, namely:

- Strong connections to – and guidance from - the target market for the direction of future development
- Opportunities for further funding by investors other than public authorities
- Greater accuracy in relation to fee structure & levels to maximise initial service uptake
- Government oversight of data integrity/ security and the maintenance of the "public good" ethos
- Focussed development of corporate structure that is more conducive to the successful development of CReDo

With an operational/advisory board made up of initial "angel" investors (possibly government representatives, consortium members and/or other industry participants), an effective connection to CReDo's target market(s) can be developed with all board members have an accurate understanding of how CReDo should be progressed to retain a level of market success. In addition, initial "angel investment" costs can be spread across all the board members, with revenue from the sale of CReDo licenses being reinvested in the continuing development of the system or distributed among initial investors so that they can recoup their outlays.

Government authorities who had previously accepted most of the financial burden for CReDo's creation would – for the most part –transfer most of their involvement in this project to a more administrative/regulatory/ advisory role.

The SME would be able to hire developers on the open market, potentially raise additional investment from other venture capital institutions, including seed investors, early-stage investors, expansion stage investors, late-stage investors, mezzanine investors, family offices, private equity investors, and corporate venture capital firms. This has the potential to dramatically increase the potential of CReDo in the open market as SME executives will be given relatively high levels of freedom to make financial and strategic decision based on a non-political understanding of where the opportunities for success lie.

Net effect on prices

Taxpayer Vs utility customer: questions of distribution, marginal utility of income and equitability

As above, the revenue model for CReDo is to be determined. In the short-term there are considerations on whether the majority of funding comes from central government, or regulator, or asset owner, or a combination.

Ultimately, if asset owners supply the revenue, those costs will filter down to utility customers. If central governmental bodies supply the revenue, those costs will ultimately be drawn from tax receipts.

In the current context of high living costs, there may be a question of equitability. It could be argued that taxpayer funding will draw receipts disproportionately from the higher income brackets (due to higher tax rates), and that their corresponding marginal utility of income is lower than for lower income households, as each £ is valued more by those on lower incomes. Thus, funding CReDo from central government departments, because the source is ultimately the taxpayer, may offer equitability benefits in comparison to having asset owners pass costs on to the utilities customers. This question remains to be explored further as part of future phases of revenue model definition and depends also on central government willingness, budget availability and departmental remit.

MANAGEMENT CASE

This section sets out governance and management arrangements considerations for this stage of delivery.

Project management governance arrangements

Managing diverse interests and technical development can come with risk and challenge. To ensure the long-term operation of CReDo, it may be worth considering the following input groups in upcoming phases:

- Decision Making Board – established to oversee development. This could be similar to the current Plenary (consortium members across industry, academia, R&D, public sector and key asset owner stakeholders), or an evolution of it.
- Technical Advisory Group – expert inputs on data governance, data security, privacy issues and exploitation of data and change control regarding standards as new frameworks, climate models and asset owner datasets emerge.
- Specialist data security advice – as risk management regarding the sensitivity of some asset owner data either on its own or in conjunction with other data sets, and inputting cybersecurity and penetration testing expertise.
- Legal advice – assisting with data sharing agreements that are scalable, replicable, efficient to adhere to and can provide a solid trust-base for sharing sensitive data, NDAs and / or managing access rights.
- Impartial direction and market co-ordination by a third party. By having a lead or facilitator without vested interests aligned to any specific sector, it may be easier to encourage true cross-sector collaboration and data sharing.

Use of specialist advisers

Fundamental to the CReDo's development has been input from:

Consortium expertise:

- Within cascade models, data hosting and architecture, data science, modelling, cybersecurity, data sharing and other considerations. Including: Edinburgh University, Warwick University, Newcastle University, Science & Technology Facilities Council
- Expertise on digital twins, strategy and stakeholder engagement with the Centre for Digital Built Britain and The Digital Twin Hub.
- Software development and modelling with CMCL.

Plenary expertise:

- Direct inputs from asset owners in key infrastructure networks across electricity, telecommunications and water.

Wider network expertise:

- Previous and future CReDo development has been guided by consultation with stakeholders in diverse sectors, from transport to public bodies to national governmental bodies and local authorities. Each bring their diverse requirements to CReDo's evolution, within the common framework of resilience to adverse weather conditions caused by climate change.

Benefits realisation arrangement

Benefits

CReDo is in early stages of prototype development and thus most benefits realisation priorities relate to securing the funding and buy-in that can take it to scale. Notable opportunities for benefits realisation extend to:

Additional use cases: leveraging the development of a working digital twin prototype for asset resilience, by extending its use cases to other adverse weather conditions that pose significant, recurring and increasing threats to infrastructure networks. Examples include extreme heat which adversely affects equipment and assets. More complex than flooding. -which often results in a binary fail or no-fail – extreme heat introduces scalar effects, whereby equipment might become partially or unpredictably compromised with degraded performance.

Additional infrastructure networks: the Strategic Case introduced the nine networks viewed by government as foundational infrastructure key to day-to-day life in the UK. Beyond water, telecommunications and electricity, CReDo has a natural opportunity to extend modelling to other networks. Priorities identified in stakeholder interviews are transport (road access, logistics, emergency access, rail) and electricity (gas is not currently included in CReDo). As per network effects (telephone networks being a good example), the more connections are introduced to a system, the more the benefits rise in a non-linear way as different permutations and impact pathways become possible / identifiable. Interviewees consistently called out energy as the most critical network for them to understand.

Impact maximising roll-out strategy

Prior to expanding use cases or scale of interconnection, benefits can be maximised by the method of scaling, and selecting roll-out via areas that offer the largest potential for economic and social impact. For example, criteria for an impact-maximising roll-out strategy could include:

1. Regions adjacent to the current pilot area in north Norfolk, in order to leverage the existing real data on networks and gain network effects in addition to the current three asset owners.
2. Regions identified as at high risk of flooding: filtered by standard flood maps, probability models and national or local flood resilience strategies. These may be areas where there is potentially a deficiency in the amount of investment into flooding containment measures compared to national averages e.g. less investment in flood defences, or where infrastructure is nearer the end of it's design life.
3. Thematically relevant networks: that mutually offer and receive benefits by modelling asset interconnectivity with existing asset owners (e.g., are additional electricity networks more relevant than local rail etc).
4. Competing networks where commercial interests may conflict. Although counter-intuitive, including competing networks may increase confidence for insurers that the cross-network cascade risks modelled in CReDo capture and represent the cross-network cascade risks in reality; and also increase data insights for regulatory users by being able to more readily compare performance across competing networks in a like-for-like manner based on comparable and consistent data.
5. Social vulnerability to flood: ensuring CReDo maximises benefits for its ultimate beneficiaries: communities, households and business. Areas can be ranked by household susceptibility and indices of multiple deprivation or other measures to identify vulnerable socio-economic groups at disproportionate risk (or who may disproportionately valuing cost savings).
6. Governmental priorities: there may be nationally strategic reasons for specific areas and regions, for example prevalence of key national security infrastructure, hospitals, military bases or other sites, installations or sensitivities. This may also include Nationally Significant Infrastructure Projects (NSIPs), such as new harbours, roads, power stations and power lines.

Risk management arrangements

Risks to the materialisation of intended economic and social impacts are discussed in the Economic Case and not duplicated here. The CReDo project operates standard risk tracking and management techniques.

Dependencies

As CReDo scales, it is dependent on timely, high quality data provision from asset owners, and climate modelling data of sufficient coverage, quality and readiness. To some extent the risk of those dependencies falls on the asset owners as they are best placed to manage their own data.

Other dependencies need to be explored in upcoming phases, such as regulatory interest in allowing data sharing and cross-sector investment in assets – whilst not currently prohibited, the structure and approval process of Price Reviews has no mechanism for including cross-sector asset investment in the outcome incentive plans or funding allocations.

A detailed view of dependencies and next steps can be seen in the project's companion document, Developing CReDo from Demonstrator to a Market-Ready Tool.

Summary conclusion

For a summary of key findings by each of the Five Cases, refer to section 1.3 "Key findings and take-aways" above.

A next phase of CReDo may wish to capture a next level of data to more fully test the expected benefits and costs, non-monetisable benefits and other considerations across the Five Cases. For example and as stated in the appropriate section above, the figures and net differences presented between the CReDo Intervention and the Counterfactual depend on a realistic Business As Usual which may be determined in future phases, as changes here will alter the expected net benefits. As such all figures are high level and indicative only at this Strategic Outline Case stage.

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